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Optical switching for future access networks

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ABSTRACT

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Access network creates a path from core network to home user of telecommunication services. It is assumed that existing access networks will be upgraded to optical networks.

Passive optical network (PON) uses passive optical components like splitter and waveguide router to path creation. PON can be arranged as along-the-route-branched or tree network structure. SuperPON uses optical amplification to better the signal quality and transmit longer distances. SuperPON is considered as an upgrade for ATM PON.

Optical switching is used in core networks cross connection devices. With optical switching systems it is possible to construct all optical transparent network. When optical switching is used in access network, management information is delivered to switches and the signal is routed to home user.

Contents

Symbols and abbreviations

ADSL	Asymmetric digital subscriber loop
APON	ATM PON
ATM	Asynchronous transfer mode
AWG	Arrayed waveguide gratings
BPPM	Binary-pulse-position-modulation
CATV	Cable television
CDMA	Code division multiple access
CO	Central office
CW	Continuous wave
DC	Decreasing coarseness
DTV	Digital television
EDFA	Erbium doped fibre amplifier
EPON	Extended APON
ES	Effective sets
FSR	Free spectral range
FTTB	Fiber to the building
FTTC	Fiber to the curb
FTTCab	Fiber to the cabinet
FTTH	Fiber to the home
HE	Head end
HFC	Hybrid fibre coax
IC	Increasing coarseness
IP	Internet protocol
ISDN	Integrated services digital network
MAC	Medium access protocol
MAI	Multiple access interference
MEMS	Micro electro-mechanical systems
MFL	Multifrequency laser
MZI	Mach-Zehnder interferometer
NIU	Network interface unit
OCDMA	Optical CDMA
OLT	Optical line terminal

ONU	Optical network unit
OOK	On-off keying
ORU	Optical repeater unit
OXC	Optical cross connect
PON	Passive optical network
PS	Potential sets
PSO	Pseudo orthogonal matrix
RN	Remote node
SDH	Synchronous digital hierarchy
SOA	Semiconductor optical amplification
SPON	SuperPON
TDM	Time division multiplexing
TDMA	Time division multiple access
VC	Virtual container
VP	Virtual path
WDM	Wavelength division multiplexing
WGR	Waveguide grating router

1 Introduction

Telecommunication services for home users demand sometimes more transmission capacity than existing copper phone lines with modem applications can offer. It is assumed that the existing copper network to home user will be gradually upgraded to optical network. This provides the additional benefit of eliminating dangers of lightning and some power line faults for example earth fault. Possible optical access network upgrades are passive optical network (PON), SuperPON and switched optical access network. Passive optical network uses power splitters to divide the signal to home users. With SuperPON access networks longer transmission distances and higher bit rates can be used because of optical amplification. Access network can be constructed also with switching or cross connection devices. One possible service, which can be implemented when FTTH is reality is DTV signal transmission over IP network. DTV signal demands about 20-30 Mbit/s transmission capacity [1] and it is assumed that FTTH could provide about 100-150Mbit/s transmission capacity [2]. When IP transmission considered the possible delay causing effects would not be anymore in access network part, but in some other part of the transmission network. It could be said that the average transmission capacity when delivering DTV signal should be above 20-30Mbit/s to provide continuous signal. Possible transmission path could consist of many networks where between the different parts of the DTV signals are delivered through different networks. Signal has to be routed also many times between networks.

Currently used commercial access networks for data transmission over the existing copper lines are called ISDN and ADSL. ISDN data rate is 128 kbit/s and different DSL techniques can provide data rates from several hundreds of kbit/s to few Mbit/s. Areas where CATV exists a cable modem can be used to receive data from cable network. With this access solution data rates of several tens of Mbit/s can be provided [3]. Access with wireless link for short distances is called local multi-point distribution services LMDS [4]. Currently available LMDS system data rates are few Mbit/s. With fiber upgrades it is possible to increase data rates to hundreds of Mbit/s.

2 Access Networks

In broad terms, an access network consist of a hub, remote nodes (RNs), and network interface units (NIUs) [5]. The hub is called central office (CO) if a telephone company is distributer and head end in the case of a cable company. Remote nodes are considered as another hierarchical level between the hub and the NIUs. Each hub may be connected to several RNs deployed in the field, with each RN in turn serving a separate set of NIUs. The network between the hub and the RN is called the feeder network, and the network between the RN and the NIUs is called the distribution network. In a broadcast network, an RN broadcasts the data it receives from the feeder network to all its NIUs. In a switched network, the RN processes the data coming in and sends possibly separate data streams to different NIUs. For example telephone network is a switched network and cable television network is a broadcast network.

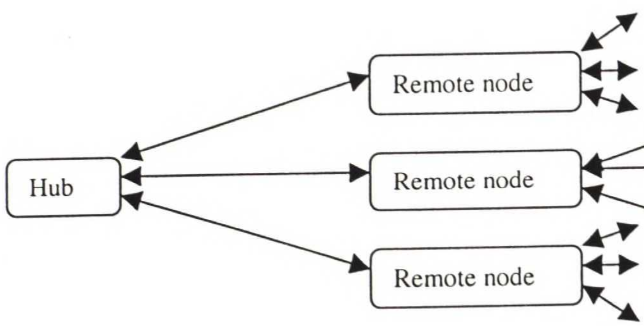


Figure 1. Architecture of an access network. It consist of a hub, which is a telephone company central office (CO) or cable company head end (HE), remote nodes deployed in the field, and network interface units (NIUs) that serve one or more individual subscribers.

2.1 Today's Access Networks

Today, two kinds of access networks reach our homes: the telephone network and the cable network [5]. The telephone network is to provide 4 kHz bandwidth to each home. The copper transmission capabilities of telephone network are intensively studied to provide more capacity for example integrated services digital network ISDN can provide 128 kb/s over the existing twisted-pair infrastructure. Fibre is pushed as close to the customer as possible because copper transmission capacity is very dependent on distances. The cable network is a broadcast network for cable television. For cable network is also possible to use some modem applications. This kind of arrangement is also called hybrid fibre coaxial HFC when transmission from HE is partly fibre and partly coaxial.

Several approaches have been proposed to upgrade the access network infrastructure to support the emerging set of new services. The integrated services digital network (ISDN) today provide 128kb/s of bandwidth over the existing twisted-pair infrastructure and is available in many metropolitan areas. Asymmetric digital subscriber loop (ADSL) is another technique that works over the existing twisted-pair infrastructure but provides significantly more bandwidth than ISDN. The realizable bandwidth is inversely proportional to the distance between the CO and the home. The DSL techniques are called xDSL, where x denotes A for asymmetric, H for high-speed and V for very-high-speed. ISDN and DSL techniques are classified as switched networks with dedicated bandwidth per NIU.

Possible upgrades to existing access networks are called FTTx, where x can be first letter from words home, curb, cabinet and so on. Also HFC is one of the terms for upgrade but its meaning differs from cable network. When existing cable network is used to for example Internet services the upstream channel has to be implemented and downstream channel cannot be broadcasting type anymore. HFC is considered as an upgrade possibility for areas where cable television network exists. Disadvantages of a coaxial-based access solutions are limited upstream bandwidth, reliability and powering needed for many amplifiers in the path. In FTTC for example data is transmitted digitally over optical fibre from the hub to remote terminating nodes that are called optical network units (ONUs). Depending on how close to home the fibre is, different terms are used to describe the access network architecture. When ONU performs the functions of NIU, which is considered as a home end of access network, the architecture is called FTTH. If ONUs serves few homes the architecture is called fiber to the curb (FTTC) or fiber to the building (FTTB). In this case, there is an additional distribution network from the ONUs to the NIUs. Feeder network is considered as the portion between the central office and ONUs and the distribution network is between the ONUs and NIUs.

2.2 Optical Access Network Architectures

Optical access network architectures must be simple and the network must be easy to operate and service [5]. This means that passive architectures, where the network itself does not do any switching in it and does not need to be controlled, are preferable to active ones. The optical networks proposed for this application are commonly called PONs (passive optical networks). PONs use some form of passive component, such as an optical star coupler or static wavelength router, as the remote nodes. Advantages of PONs are reliability, ease of maintenance and the fact that field-deployed network does not need to be powered. A simple PON architecture is a point-to-point PON, which uses separate fiber-pair from CO to each ONU. Logically there is a separate fiber-pair to each ONU, physically the fibers could be laid in a ring configuration. Instead of providing a fiber-pair to each ONU, a single fiber can be used with bidirectional transmission. There are two alternatives for bidirectional transmission with a single fiber. Data transmission simultaneously from both ends would cause uncontrolled reflections in the fibre. One possibility is to use time division mode when both ends do not transmit simultaneously. Another possibility is to use different wavelengths for the different directions.

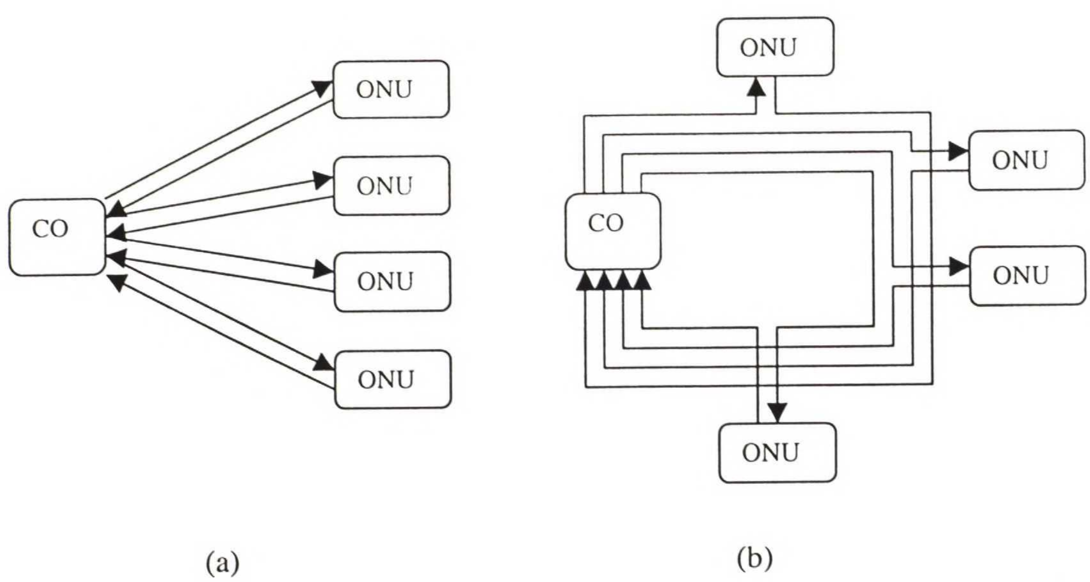


Figure 2. (a) The point-to-point fiber approuch. (b) In practise the fibers could be laid in the form of a ring.

3 Passive Optical Network

Passive optical network (PON) is one of the proposed possibilities to upgrade current access network. PON can be implemented with splitters, which split the signal power to many parts but do not affect other signal parameters. Access network is considered as passive when the network does not perform any signal processing for example reading header information or switching when signal is transmitted from exchange building or central office (CO) to optical network unit (ONU) which is considered as home user end. At the moment standard telephone lines and ISDN-lines are used to data transmission to home user with capacity 64 kbit/s and 128 kbit/s. For small offices and private homes service rates can be very expensive if there are lots of communication needs. In some calculations [2] 155 Mbit/s optical subscriber line, which is open all the time, is more feasible access solution than ISDN.

3.1 Along-The-Route-Branched Passive Optical Network

In [2] three PON structures are compared. Important features for PON access are integrability, upgradeability and installation. Integrability tells how easily new customers can be connected to implemented PON. Upgradeability means possibility to alternate the PON to support more capacity demanding services. Installation tells how easy it is to replace the current access network with new PON structure. Three alternative PON structures was compared, which were full-star, 1-point-branched and along-the-route-branched. Along-the-route-branched (Figure3) access network architecture was found to be suitable for small offices and private home areas. The cable can be a 2-fiber ribbon duct or aerial cable. The 2-fiber pair (one for upstream and one for downstream) is branched by fusion splicing with two passive standard fused fiber couplers (with coupling ratio 10/90 or 20/80), or by the new passive branching component, along the route. Each house can be reached from the branching points by a similar 2-fiber cable, which has connectors at the other end for the transceiver to be installed inside the house.

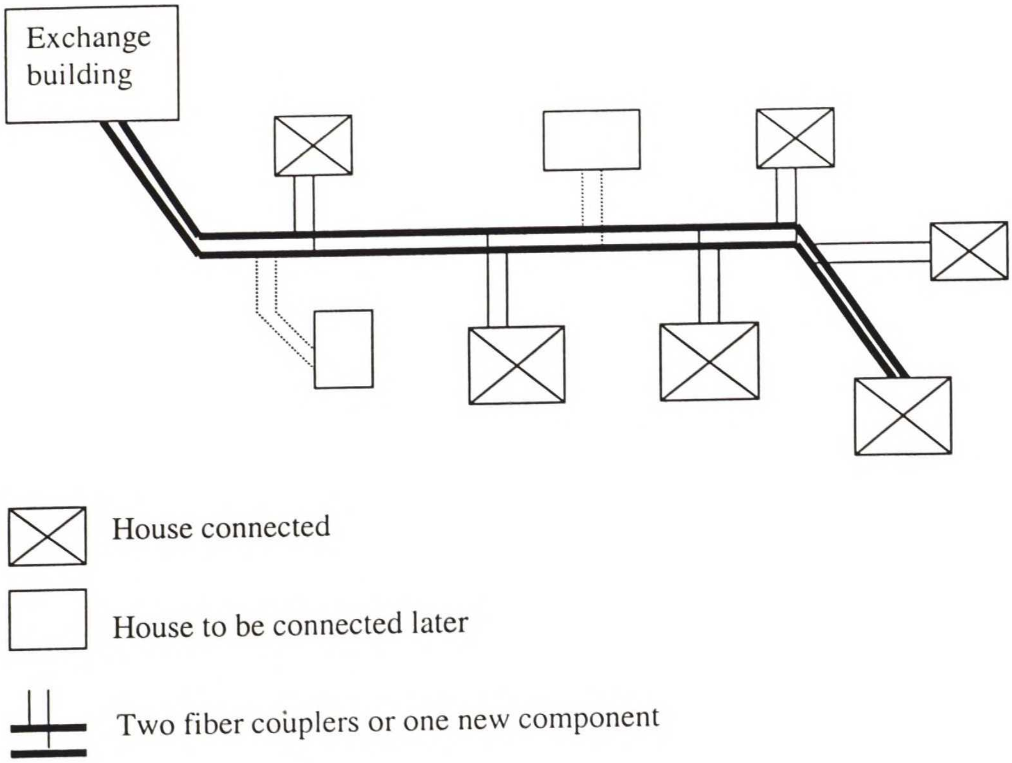


Figure3. An integrable, along-the-route-branched FTTH-network structure.

3.2 Arrayed Waveguide Gratings

If passive optical access network is implemented with splitters and TDM power splitting can be problematic in large scale access network. Another possibility is to use wavelength division multiplexing WDM with arrayed waveguide gratings AWG. AWG is a network element which can route wavelenghts from input WDM signals to output WDM signals. In [6] is a WDM-PON access network with AWG routers arrenged in tree network structure to provide all optical access from CO to ONU in home. Each home user has own wavelength channel and there is no signal power splitting as there is with TDM-PON. Tree network structure between CO and ONU means that WDM-signal transmitted from CO is divided to ONU:s using multiple stages of AWG:s. In time division multiplexing time slots are distributed to different users. Although this also means that each user in the access network gets the same data from which the particular data for each user have to be specified and collect. There is also access to all the data transmitted with fibre in every ONU if TDMA is used. So security issues are poor. With WDM access there is a wavelength to every user. So other users data will not get to every ONU in the access network.

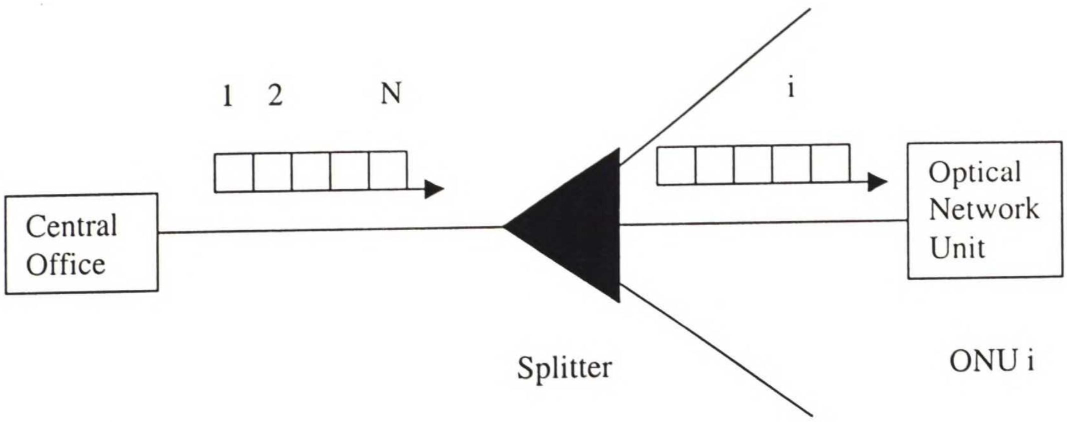


Figure 4. TDM-PON FTTH network structure.

For a WDM equipment can be defined free spectral range. Waveguide grating router WGR behaves like a passing-band periodical filter, its power transfer function having peaks repeating at a fixed wavelength interval called free spectral range (FSR). The power transfer function of WGR is considered to have M peaks in the free spectral range having a wavelength interval $\Delta\lambda$.

$$FSR = M\Delta\lambda \qquad (1)$$

The second parameter to characterize a WGR equipment is called coarseness C and represents the number of contiguous wavelength channels belonging to the wavelength comb (i.e. spaced by an interval $\Delta\lambda$) routable to the same output port. The coarseness corresponds to the optical resolution of the device. WGR equipment used in tree network WDM-PON architecture can be specified with two parameters M and C.

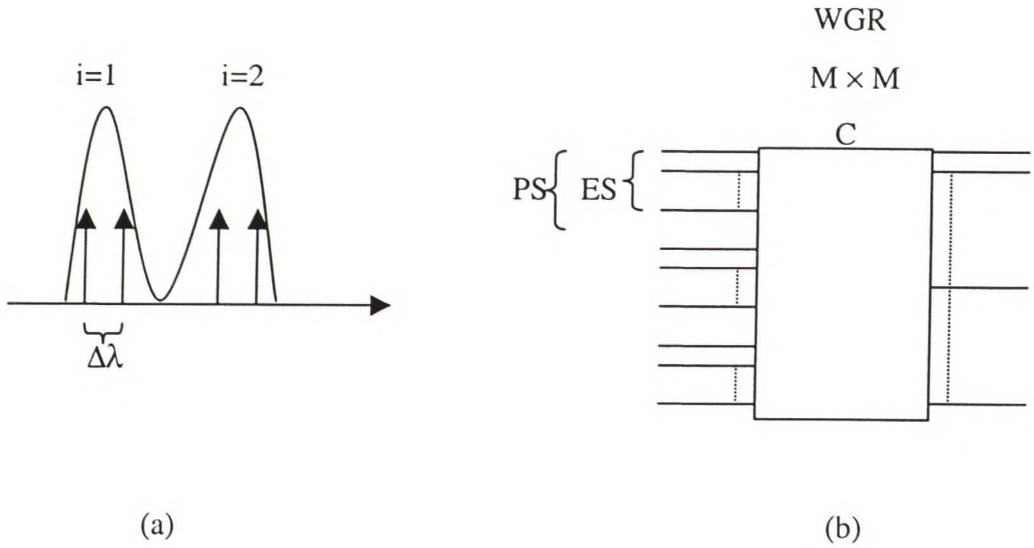


Figure 5. (a) Transfer function of a WGR device when M = 2 and C = 2. (b) WGR device with inputs divided to potential and effective sets.

WGR devices inputs were divided to effective sets (ES) and potential sets (PS). PS is the total amount of input ports and ES is the amount of used input ports in the PON structure. WGR devices input ports are divided to multiples of potential sets. In each input port there is a possibility to use C wavelengths. It is assumed that all input ports in WGR device in stage k are never used. Two WDM-PON cases were considered. The other has a property of increasing coarseness (IC), which means that the amount of wavelengths in each input port of WGR devices is increasing when moving to downstream direction in PON architecture. IC is achieved if ES in WDM-PON structure is considered to consist only one port. Another property of PON is decreasing coarseness (DC) and this can be achieved if PS of WGR devices consist of all the input ports.

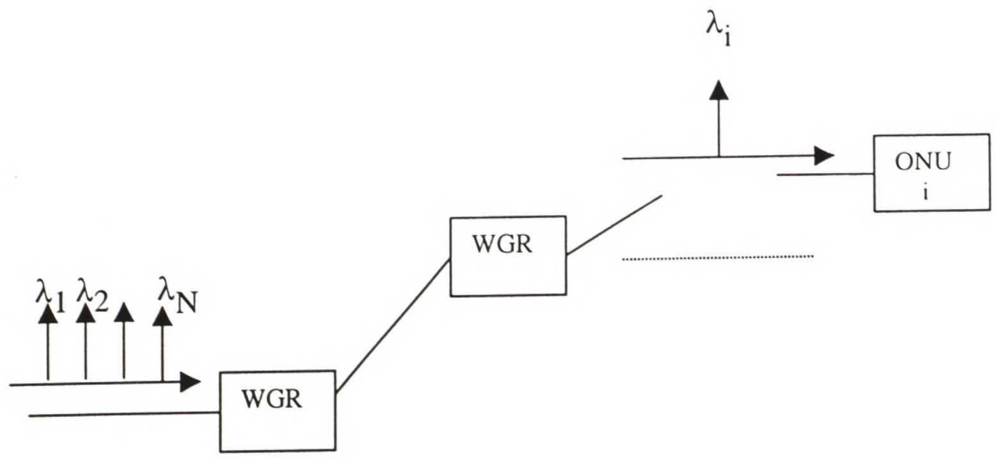


Figure 6. WDM-PON FTTH network structure.

3.3 Fast optical switching in WDM passive optical access networks

In [7] a WDM-PON is presented using cross connection between OLTs and ONUs for IP-based services. Two options for mapping optical packets between ONUs and a number of OLT transceivers by means of an optical cross-connect (OXC) is considered. The other option uses fixed wavelengths at the OLT transceivers and flexible wavelengths at the ONUs. Flexible wavelength source requires multi-wavelength laser while fixed WDM assigns one laser per WDM channel. Data packet transmission and receiving at the OLT happens at fixed wavelengths, so one WDM channel transmits and receives data of several ONUs. If flexible wavelengths are used ONUs have to be able to receive data from several WDM channels. In the experiment 16 ONUs share a single wavelength channel and 8 channels are multiplexed per fibre by using passive arrayed waveguide gratings (AWGs). The other option uses flexible wavelengths at the OLT transmission and receiving and fixed wavelengths at the ONUs. For example in the upstream data transmission a WDM channel in fibre is shared by 16 ONUs. One ONU transmits a data packet to one of the 8 WDM channel which is shared with other ONUs by TDMA. ONU lasers are now fixed to a certain wavelength channel while OLT lasers are operating with multi-wavelength lasers transmitting and receiving data from several WDM channels. The option which uses fixed wavelengths at the ONUs and flexible wavelengths at the OLT is considered better because optics in the ONUs is simpler and the switching optics is located at the central office.

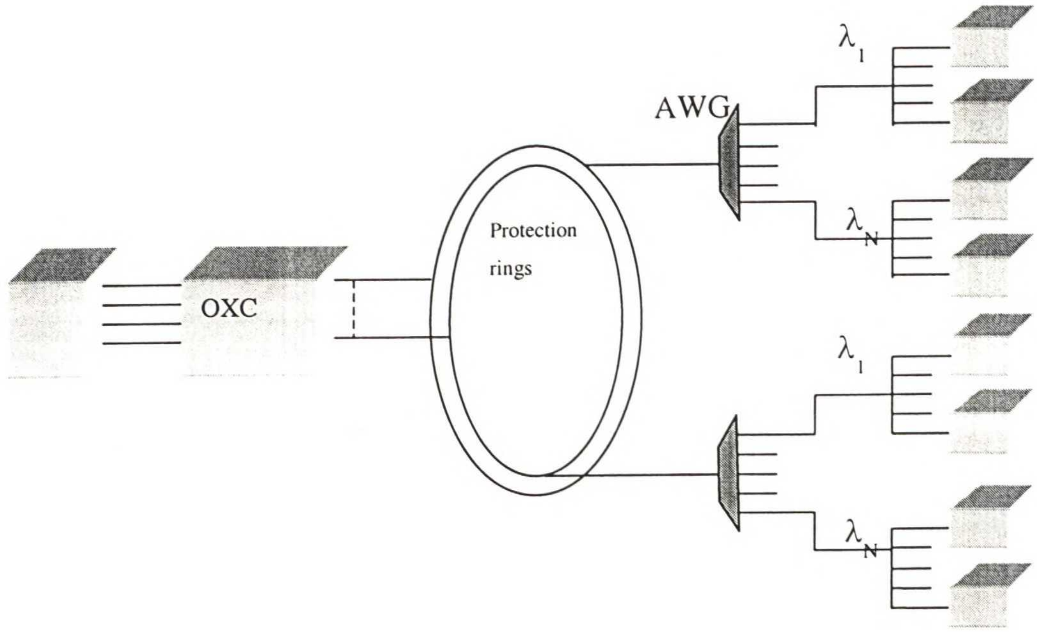


Figure 7. Optical feeder network.

4 SuperPON

Super PON is a PON architecture where optical amplification is used to better the signal quality and also make possible to transmit longer distances. Optical amplification can be implemented for example with semiconductor optical amplification SOA or erbium doped fibre amplifier EDFA. It is also possible to increase splitting ratios of splitters when amplification is used and in this way achieve larger access network. In some experiments [8] about 30 million homes could be reached with SPON access. Currently available PON structure is called ATM PON or APON [9]. This APON structure can be upgraded to SPON when components for implementing super PON are available commercially. In APON implementation bandwidth which can shared between different ONU is 622Mb/s or 155Mb/s in the downstream direction and 155 Mb/s in the upstream direction.

4.1 The SuperPON demonstrator

Upgrading APON to SuperPON is mainly motivated by three factors [9]. The increase in range can support the expected switching node consolidation in the core network and result in cost savings for the operation of the network. The fiber-to-the-cabinet plant can be extended to the home by inserting an optically amplified splitter. If such a deployment were to take place with conventional APON technology, more fibers and a higher number of line termination boards would have to be installed. The gain in bandwidth efficiency due to statistical multiplexing increases with the number of users connected to a single line termination. The SuperPON architecture supports a long range, a high splitting factor, and a large bandwidth capacity. Advantage of optical amplifiers compared to electronic devices is their transparency to format, bit rate, and wavelength, and their simple management. The realized experimental SPON system parameters are a total splitting factor of 2048 and a span of 100 km. SPON system can serve 2048 ONUs in 100 km distance. The transport system supported on the SuperPON is based on asynchronous transfer mode cells. A downstream bit rate is 2.5 Gbit/s and time division multiplexing (TDM) is used to deliver the data to ONUs. Upstream bit rate is 311 Mbit/s and time division multiple access (TDMA) protocal is used to share the upstream bit rate. The optical amplifiers are housed in optical repeater units (ORUs). They are located at the feeder section (feeder repeater) and at the intersection between the feeder and the drop sections (amplified splitter) to compensate for the fiber and splitting ratio losses.

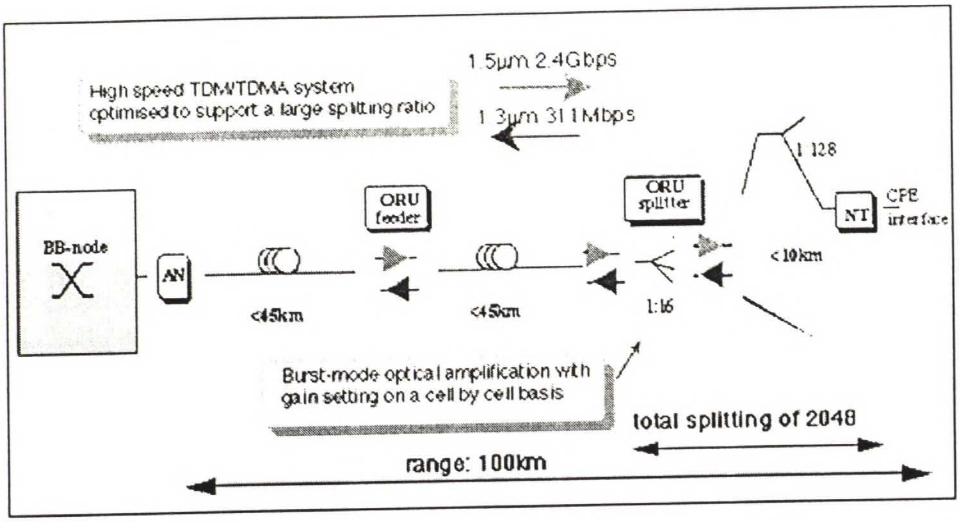


Figure 8. The experimental SuperPON system.

In the SuperPON system two types of cells are supported in the upstream direction, namely, data cells that transport ATM cells, and mini-slots that can transport data of four bytes long. The mini-slots can, for example, be used for polling of the ONUs. As the downstream communication operates in a continuous wave (CW) mode, erbium-doped fibre amplifiers (EDFA) are used. These amplifiers feature a low noise figure and a high gain. EDFA amplifiers are characterized by a large time constant and that is why they are difficult to use in the upstream direction due to the bursty nature of the traffic originating from the ONUs. In addition, the upstream optical amplifiers located at the splitter should be switched on only when a TDMA packet passes through. The semiconductor optical amplifiers (SOAs), which in essence consist of a laser structure without mirrors, offer the advantage of being switched on/off on a nanosecond time scale.

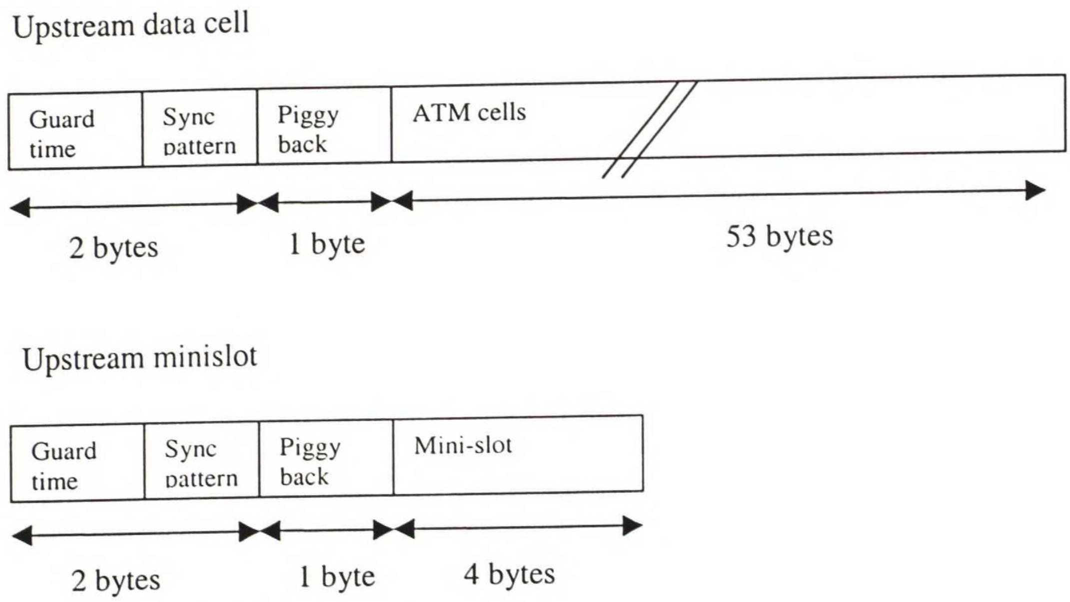


Figure 9. Overview of the upstream cell formats.

4.2 Medium Access Protocol

A PON system can be considered as distributed multiplexer that multiplexes ONU streams at the OLT and ATM-based VP/VC streams at the ONU [9]. Central control system called Medium Access Protocol (MAC) for OLTs is used to assure high efficiency and prevent collisions in data stream multiplexing. The principal function of the MAC protocol is the MAC algorithm, which generates the permits. In the SuperPON system MAC algorithm consist of a rate-based generator, which generates permits at a fixed rate, based on signaling information. In the SuperPON system two types of MAC channels are supported in the upstream data frame. The first is polling channel, which uses mini-slots to poll the ONUs as quickly as possible. The second MAC channel is called piggy-backing, and consist of an overhead byte in front of each upstream cell. This piggy-backing is especially needed for the SuperPON system, since the efficiency of the polling is limited due to the great number of users in the system. The third building block of the MAC protocol is the cell-scheduling algorithm at the ONU. This algorithm will decide which cell will be sent when the ONU receives a permit to access the upstream channel.

4.3 Feasibility of SuperPON

The economic feasibility of three PON technologies are compared for FTTCab and FTTH: APON, EPON (extended APON) with increased splitting factor or range, and SuperPON with increased bit rate, split, and range. It can be concluded that the cost of a FTTCab network based on SuperPON technology is comparable to the conventional solution using APON + SDH. However, the advanced PON architectures contain many optical components, the costs of which will decrease faster than for the APON + SDH solution. SuperPON offers greater network planning flexibility because of its longer range and the small size of the optical amplifier cabinets. For the FTTH case, solutions using SuperPON technology appear to be slightly more economical than APON [9].

5 Optical Switching

Another possibility to provide fibre access is to use optical switching. When optical switching is used some kind of management for switches is needed so the network is not passive. Management could be arranged so that the management information is delivered with the actual data to the switching element or management information could be delivered some other way. Optical switching is useful for example for Internet traffic because transmission is not delivered to every ONU as is the case with some passive optical networks, but switched to a specific destination. In WDM-PON implementation with AWG routing each user has his own wavelength channel, so when data is transmitted from CO to user it is sent with defined wavelength to this user. There are various techniques to construct an optical switch. These techniques are also used to implement large cross connection devices without optical to electrical conversion. Construction techniques of optical switches are divided to integrated, all fiber, micro-optic and hybrid.

5.1 Titanium Diffused $LiNbO_3$ Electro Optic Switches

Titanium diffused $LiNbO_3$ electro optic switches are examples of integrated optical switches. In switching and cross connection construction usually large switching devices are build by connecting smaller switches. In [10] 2×2 integrated electro optic switch was build from which it is possible to construct larger switch.

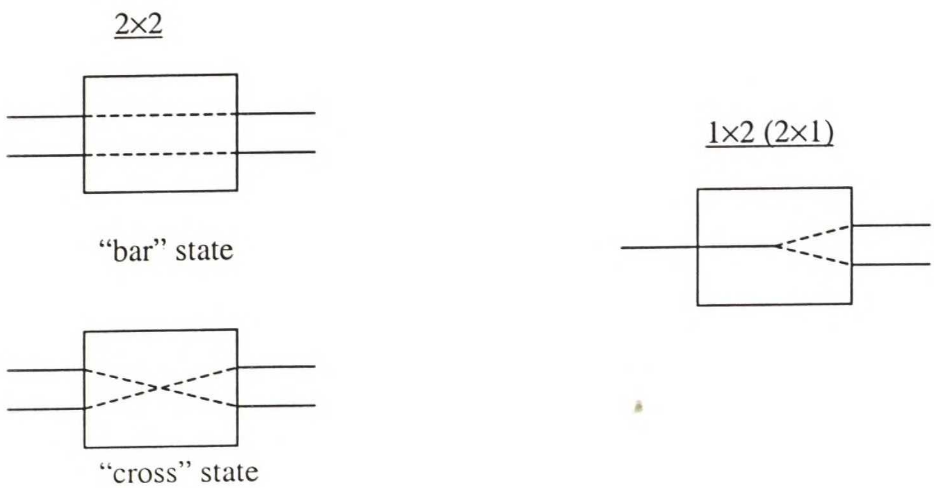


Figure 10. Switching states of a crosspoint for 2×2 and 1×2 (2×1).

Crosspoint switch elements are selected in use of switch array circuits and systems under consideration: Does switch operate as a 2×2 or an 1×2 (2×1)? How much crosstalk does it have? How much (voltage × length) product does it have? Are the switching characteristics sinusoidal or digital? Does it have polarization and wavelength dependence? Does it have enough stability? There are specific issues which have to be considered when integrated electro optical switches are constructed. These are packaging and stability. Packaging is the most important technology to complete waveguide devices to be supplied to the systems and fields. Stability issues to consider are optical damage/photo-refractive effect, thermal drift caused by the pyro-electric effect, dc-drift: long term driving point drift and unstability caused by packaging.

5.2 Arrayed Waveguide Gratings

Wavelength routing can be performed in the optical domain for both long-haul and passive optical network [11]. Arrayed waveguide gratings (AWG) can perform wavelength routing for a large number of optical channels and provide a high level of functionality on an integrated chip.The AWG guides light on a planar lightwave circuit into an array of waveguides that provide dispersion to separate the different wavelengths of light. Routing functions can be performed on individual wavelengths. Wavelength-division systems (WDM) are evolving from point-to-point systems to transparent optical networks (also called photonic network). A transparent network routes wavelength channels without electro-optic conversion.

Routing of a wavelength between input and output ports can be described with a equation (2), where p is input port and q is output port. λ is a wavelength of an input port p belonging to wavelength comb defined by coarseness C in equation (1). λ_1 value is characterizing the WGR device including light propagation distances within the device and collimation angles.

$$\lambda_{p,q} = [\lambda - FSR] - [(p+q)\lambda_1 - FSR] \qquad (2)$$

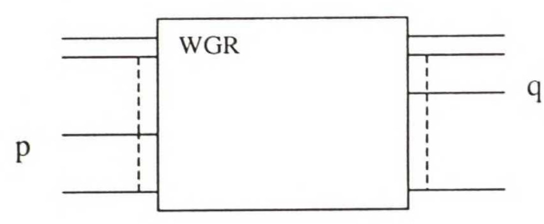


Figure 11. WGR device with input port p and output port q.

An application of optical switching is transparent optical cross connecting. An OXC can be constructed with N discrete AWGs acting as demultiplexers, N discrete AWGs acting as multiplexers, and M optical space-division switches in between. An integrated 2×2×4 silica-based OXC uses four MZI thermo-optic switches and only one AWG in loopback configuration. In this configuration, each wavelength passed through the AWG twice in the same direction before entering the output fibre. In the first pass, the AWG acts as a demultiplexer; in the second pass the AWG acts as a multiplexer. An optical signal arriving to the input port A is demultiplexed to four output ports of the WGR device according (2). In the example there are two wavelengths arriving to port A and the wavelengths are routed to output ports in the figure 10 when AWG acts as a demultiplexer. The routes of wavelengths are described with dashed lines. There are four switching devices included in the structure of OXC, which perform the switching of demultiplexed wavelengths. The two wavelengths arrived to the input port A are switched so that the other leaves from the output port A' and the other from B'. After switching wavelengths are multiplexed according (2).

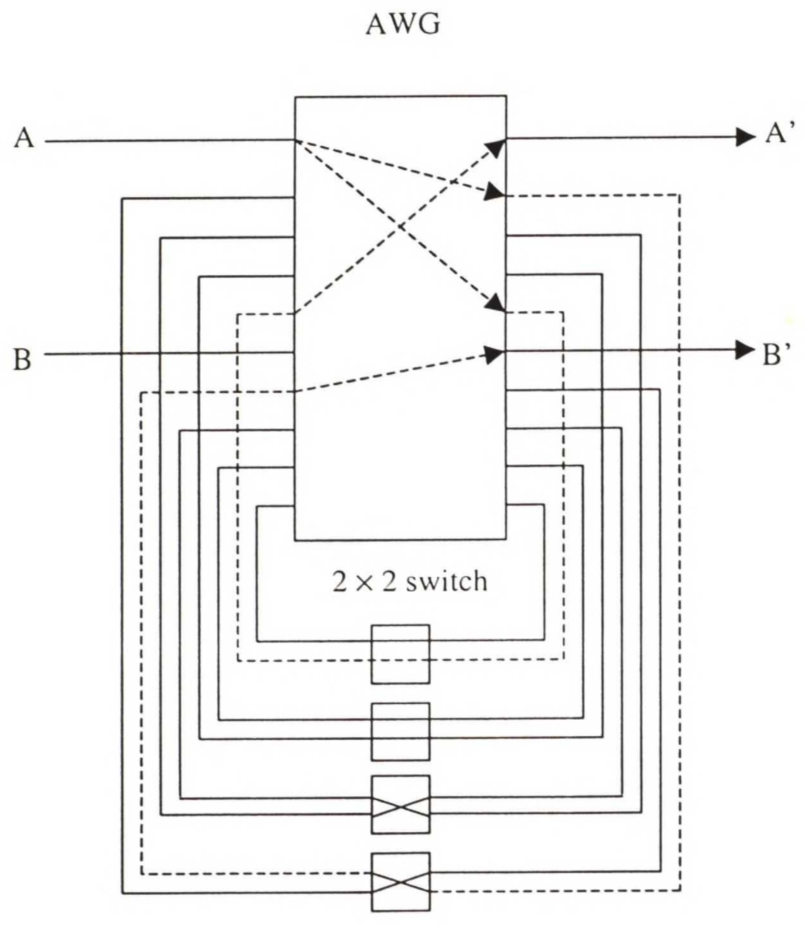


Figure 12. A 2×2×4 OXC can be constructed with a single 10×10 AWG in loopback configuration: one wavelength channel is crossed over from A to B'; the other is not crossed over.

5.3 Micro Electro-Mechanical Systems (MEMS) Erected On Si

Switching by micro electro-mechanical systems (MEMS) erected on Si is micro-optic technology used for optical switching [12]. This micro electro-mechanical system uses a control voltage to decide whether the switch is in cross state or in bar state. When the switch is in cross state control voltage is used to pull up the mirror. When the voltage is zero the mirror is pulled back with suspension springs. The simplest configuration to build a 2×2 switch uses only a double-side reflection mirror. In the bar state the light out of two pairs of fibers is coupled in a straight path between the fibers no.1 to no.3 and between fibers no.2 and no.4. To switch in the cross state the micromirror is brought into the optical path.

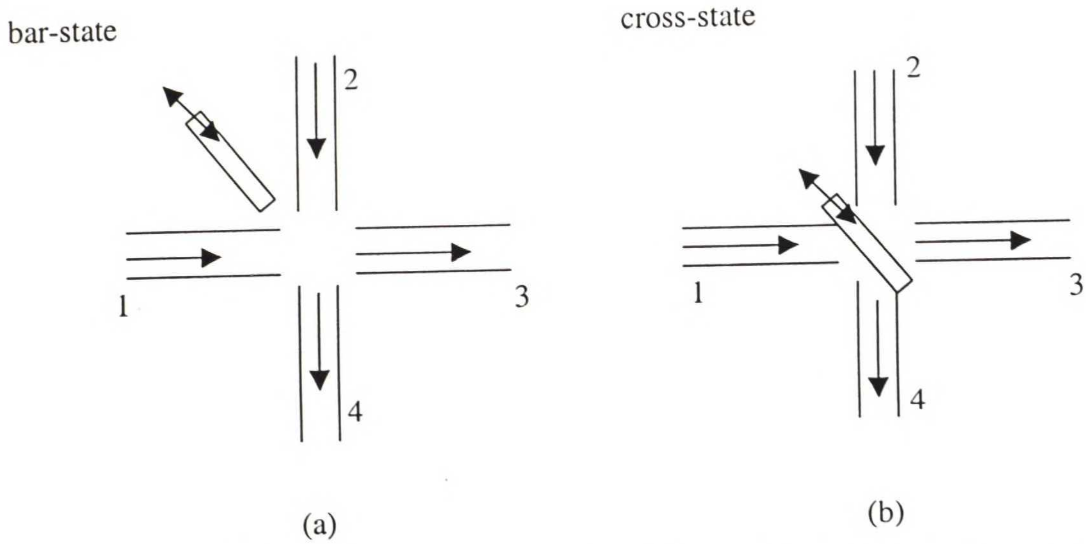


Figure 13. Schematic top view of a micro-mechanical 2 × 2 switch. In the cross state the light beam is reflected on the vertical mirror (b). In the bar state, light travels in a straight way (a).

6 Multiplexing Methods

With multiplexing information signals can use same transmission channel. Time division multiplexing system collects signals from different information sources at certain time moments. The receiver of TDM system combines the original signal with the knowledge of time slot duration. Wavelength division multiplexing uses effectively transmission capabilities of optical fibre because several wavelength channels are transmitting signals. WDM is considered useful for core network high capacity transmission. Bidirectional access network can be constructed by using two channel WDM. It is also possible to use optical code division multiplexing in access network between CO and ONU. For each user in access network a code is assigned, which is used to multiplex the signal to transmission channel. In the ONU the code is used again to demultiplex the signal. Other signals in the access network, which are arriving to ONU are considered as noise. Security issues are now better than in time division multiplexing or wavelength division multiplexing because it is difficult to demultiplex the signal without knowing the code which has been used to spread the data signal. Since OCDMA is multiplexing method in which many users are using same frequency channel then the multiple access interference MAI is the main cause of errors.

6.1 OCDMA Systems

6.1.1 Turbo Encoded OCDMA System

Code division multiple access has several benefits compared to other multiplexing methods: 1) asynchronous access capability, 2) accurate time of arrival measurements, 3) flexibility to user allocation, 4) ability to support variable bit rate and bursty traffic, 5) security against unauthorized users, and 6) anti-jamming capability [13]. The turbo code is a kind of concatenated convolutional coding technique, and it performs decoding in an iterative manner. The encoder is formed by concatenating two constituent codes in parallel and separating the codes by interleaver. Two encoders operate with the same set of input bits u. Coded bits v_1 and v_2 are fed to the puncturer, which can be used for adjusting the code rate by periodical deletion of coded bits.

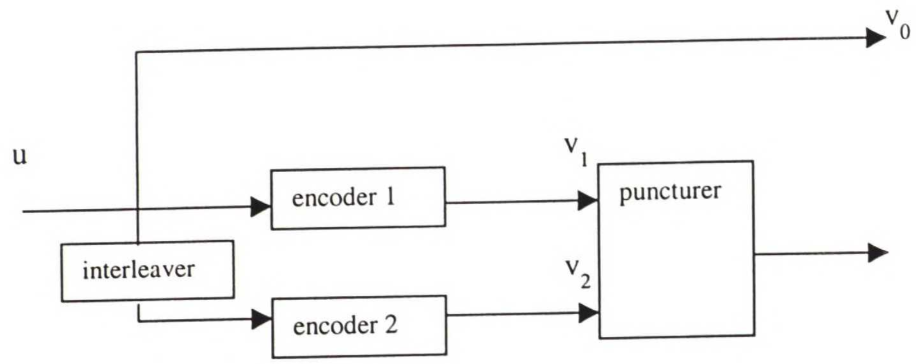


Figure 14. Turbo encoder.

In the OCDMA system the information bits of each user are fed into the turbo encoder. The turbo encoded bit stream is modulated at the Binary-pulse-position-modulated (BPPM) modulator where the transmitter sends its pulse sequence in one of the two time slots (symbol positions) to represent each data bit. In laser pulse transmitter, the laser is pulsed on at the first chip position corresponding to the symbol. The received signal is first processed in the optical correlator and the correlator output is converted into the electrical signal at the photodetector. In the BPPM demodulator, the highest output of two slots is selected as the transmitted symbol, then is passed through the turbo decoder to estimate the transmitted information bits.

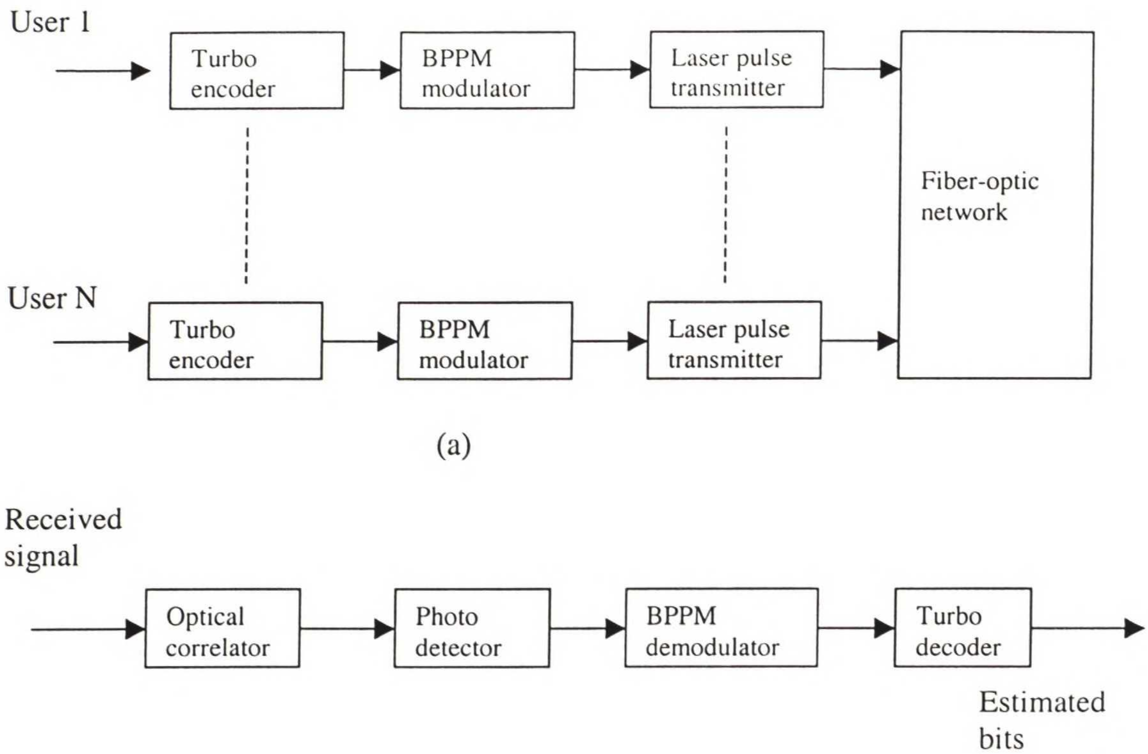


Figure 15. Block diagram of Optical CDMA system: (a) Transmitter. (b) Receiver.

For each user in the OCDMA system is assigned an optical orthogonal code with desirable crosscorrelation properties for multiple access interference reduction.

6.1.2 Pseudo Orthogonal Matrix Codes

In [14] OCDMA system for dense (>eight users), high speed (>>155 Mb/s), long span (>>40km) optical networks is described. Pseudo orthogonal matrix (PSO) codes are introduced, which are designed to operate at 2.5 Gb/s data rates and to incorporate dense WDM Multifrequency lasers (MFL). One or more PSO sequences are folded or converted into a two-dimensional matrix so as to preserve the correlation properties. The columns are associated with time slots or chips while rows are associated with wavelengths. A "one" within the matrix corresponds to the transmission of an optical pulse at that wavelength and in that time slot. Thus a matrix code is physically generated as a set of pulses at specific wavelengths and time slot times. The width of the matrix (number of columns) therefore denotes the code bit time, and conversely, the bit time divided by the number of columns is the required chip time of the matrix code.

$$[1010011] \rightarrow \begin{bmatrix} 101 \\ 00- \\ 11- \end{bmatrix}, \begin{bmatrix} -11 \\ 101 \\ 00- \end{bmatrix}, \begin{bmatrix} -00 \\ -11 \\ 101 \end{bmatrix}$$

Figure 16. Folding of PSO sequence to two dimensional matrix.

PSO sequences have correlation benefits, which can be remained if folding and cyclic row-shifting are used. In figure 16 is presented a PSO sequence of length seven, which is folded to two dimensional matrix. Additional matrices are generated by two downward shifts. PSO sequence coded symbol corresponding the first two dimensional matrix is transmitted with four pulses each pulse denoting one in the matrix. For two dimensional matrix with three rows and three columns there are wavelengths λ_1, λ_2, λ_3 and three time slots t_1, t_2, t_3. Four pulses are transmitted with three wavelengths so that a pulse is sent with λ_1 and λ_3 at time slot t_1, a pulse is sent with λ_3 at time slot t_2 and a pulse is send with λ_1 at time slot t_3.

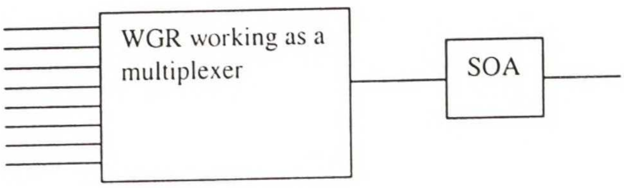


Figure 17. Multifrequency laser transmitter for PSO OCDMA system.

The MFL consist of eight individual gain sections coupled through a wavelength grating router to an output port. The system uses eight wavelengths and each sending pulses according eight times eight PSO matrix. These eight independent cavities may be coupled to the output fiber by means of semiconductor optical amplifiers (SOAs).

6.1.3 Frequency spread coding

Frequency spread coding is multiplexing method used in radio communication. With frequency spread coding, each data symbol is transmitted with more than one sub-carriers and thus achieving frequency diversity [15]. In optical communication frequency spreading can be considered as WDM. Data symbols are coded and transmitted with different wavelength channels. Diversity is achieved now by transmitting coded data symbols with more than one wavelength channel. This differs from PSO sequence transmission in which chips of coded data symbol were divided to wavelength channels.

6.1.4 Multiaccess Interference

Multiaccess interference (MAI) is caused by other codes that have pulse overlaps with the desired code [14]. This occurs randomly due to the data modulation and the asynchronity (time offset) of the encoded signal. There are three categories of MAI reduction strategies. The first uses a threshold for on-off keying (OOK) decoding. Statistics of MAI randomness is used to derive this threshold, so this MAI reduction method is only as accurate as the randomness model, and suffers in performance by the large variances caused by many users with their independent usage statistics. The second estimates code interference over long time period, and then decoding is accomplished by passing the same observations through a decoder adjusted by the MAI estimates. The third reduction technique attempts to estimate the MAI in real time from the non signaling positions of the desired code during each bit period. This technique is developed to avoid bit decoding delay with the second interference suppression method when interference is estimated over a long interval.

6.2 Subcarrier multiplexing

Optical subcarrier multiplexing (SCM) is a scheme where multiple signals are multiplexed in the RF domain and transmitted by a single wavelength [16].

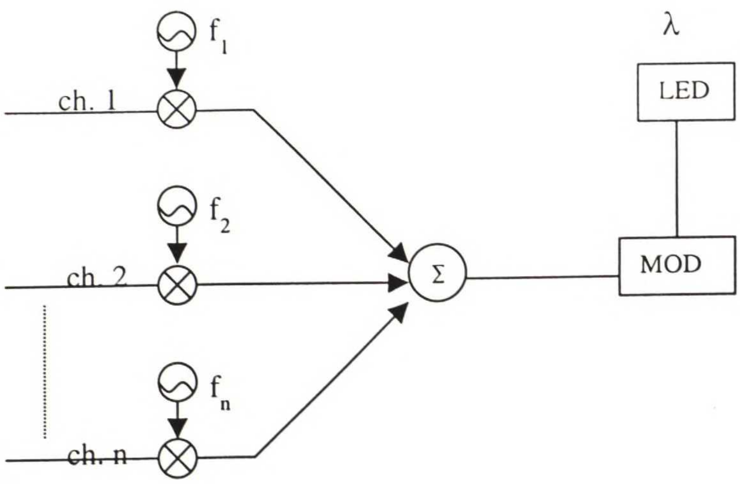


Figure 18. SCM transmitter

Data channels with 2.5 Gbit/s were mixed with microwave carriers from frequency spectrum 3.6 GHz to 18 GHz.

6.3 Polarization multiplexing

Polarization multiplexing can be used to increase data rates as well as SCM and WDM [17]. Polarization shift keying is a multiplexing scheme where bits are transmitted from a single word-generator in either one of two polarization stages or on multiple polarization stages. Polarization division multiplexing uses independent data sets on each of two orthogonal optical polarization states. Transmitter of polarization division multiplexed system uses two binary phase shift keying data sets, which are multiplexed to orthogonal polarization states. The other data set is carried with transverse magnetic (TM) optical signal and the other is carried with transverse electric (TE) signal. Two orthogonal polarization states are combined in polarization combiner.

7 Optical Switching network Architectures

In optical switching larger switching elements are usually constructed from small switches like 2X2 or 4X4 switches. From these switches it is possible to construct switches over 100X100. This can be done with for example multistage switching networks. Clos network is the best known multistage switching network. Clos network is based on Clos theorem for multistage networks. Usually Clos network is used as a three stages network and then the strict sense non blocking functionality of the network is achieved. Clos network has an input stage from which there is a connection to every switch in the next stage from which there is a connection to every switch in the next stage and so on.

Blocking is an important feature when larger size switches are built from smaller switches with multistage networks. Strict sense non blocking network is one possibility and this means that when new connection is made from input stage to output stage there is no need to make changes in already existing connections between stages. Changes in already existing connections would cause interruptions in traffic which is transmitted through the switch. Rearrangeably non blocking network is possible when short interruptions in traffic are not essential. In rearrangeably non blocking network when a new connection is established this new connection can be done with changes in already existing connections. Rearrengeably non blocking network requires less switching elements to achieve same capacity switch than the strict sense non blocking switch but there can be interruptions in traffic. For example if there is a connection path in three stages network from input stage to output stage and a new connection has to be established so that the already existing connection has to be rerouted.

In a blocking network it is not possible use all the available input and output connections because the network has not enough switching elements to provide connection paths to every input and output lines. Wide-sense non-blocking network is a term used when it is possible to set any new connection provided that a given path searching algorithm is used [18]. The algorithm decides which connection path is used through the network so that future connections are not blocked and the maximum network capacity can be used. Strict sense non-blocking network is non-blocking whatever routes are made when a connection is established.

7.1 One-Sided Two Stage Bidirectional Network

When the switching network is illustrated the connections are considered as a flow from an input stage to an output stage. Although connections can be bidirectional as is the case for example when a wavelength is assigned to communication in upstream direction and other wavelength assigned to communication in downstream direction in WDM based system. Bidirectionality can also be achieved if different fibres are used for upstream and downstream direction in a switching network. A possible bidirectional switching network architecture is one-sided two stage bidirectional network [19]. One-sided means that outer connection terminals are arranged to either of two stages. The second stage acts only as a switching stage also called distribution stage. When a connection is established from input terminal in one switch to output terminal of other switch, a route through network is made. A signal arrived at one of the inputs in the first stage is switched to one of the outputs in the first stage switch. If there is an algorithm to choose routes through network, there has to be information in every switch for choosing the output terminal. Routing algorithms are used in wide sense nonblocking networks. With routing the amount of distribution switches can be decreased.

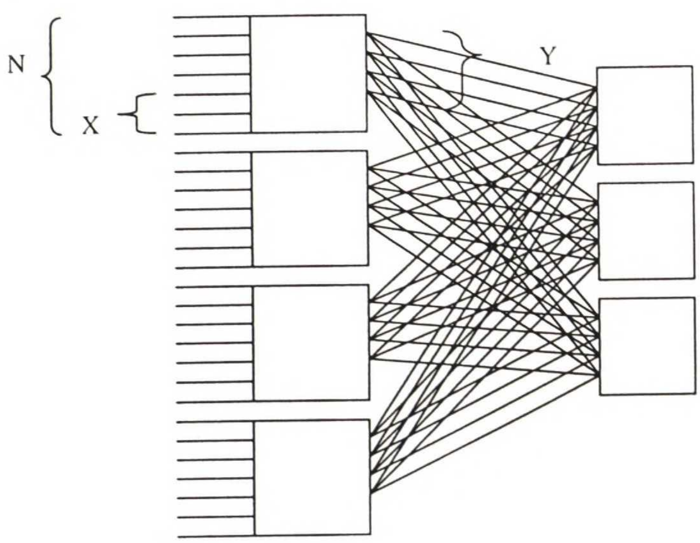


Figure 19. One-sided two-stage bidirectional switching network.

For one-sided bidirectional two-stage network it is possible to derive a formula for the amount of middle stages nodes. For strict sense nonblocking network a formula can be derived from the worst case connection situation. The worst case connection situation can be defined so that if there are N output/input ports in each first stage switching element. A connection is made through network when N-1 input ports are used to other connections in this particular switching element and N-1 output ports are used to other connections in the destination switching element. Connections are made so that each route through network demands one second stage switching element. So there has to be N-1+N-1+1 second stage nodes to achieve strict sense non-blocking structure of network.

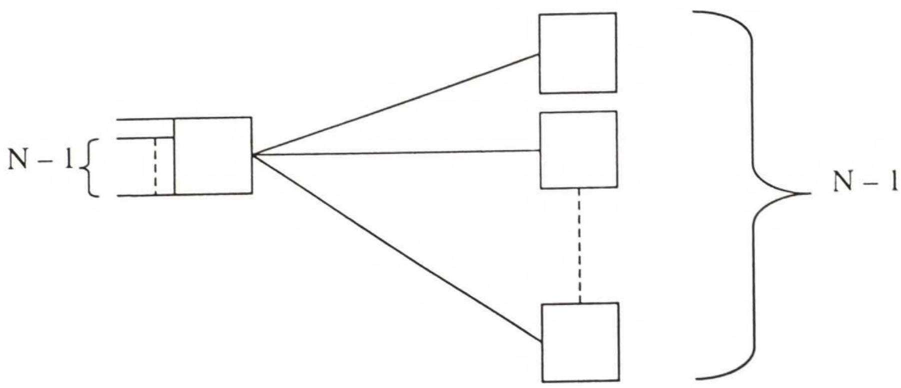


Figure 20. Each route through network demands one second stage switching element.

This formula can be used when there is one connection between first and second stage nodes. For multiple connections between first and second stage, the number of connections could be marked with Y. If the bandwidth of one connection between first and second stage is A bit/s, for multiple connections bandwidth between stages is Y*A bit/s. If there are N outer connections in each first stage switching element, the bandwidth used is N*A bit/s. N can be considered as a sum of multiples of Y*A bit/s connections and additional connections, which can be denoted by X (X=1,2,3,…,Y) and these require bandwidth X*A bit/s. Outer connections can be marked N=Z*Y+X, when assumed N > Y. Bandwidth can be normalized to C bit/s = Y*A bit/s by making the division N/Y=N'/Y+X/Y and the expression for required second stage nodes is now (N – X + N – X)/Y + 1 = 2*N'/Y + 1 = 2/Y*(N – X) + 1 by the definition of the worst case connection situation and because X <= Y.

7.2 Folded Clos Network

Bidirectional one-sided two-stage switching network can be considered as a folded bidirectional three stages Clos network, where the third stage has been put part of the first stage. If strict sense non-blocking three stages Clos network in figure 21 is folded, the strict sense non-blocking property is maintained. The connections in three stages Clos network are considered as a path from the input stages node to the output stages node. If the network is bidirectional input stage can also act as an output stage and output stage as an input stage. In the figure 15 nodes A, B and C are input stage and nodes D, E and F are output stage. Connections can be made for example from node A to F and from node D to C.

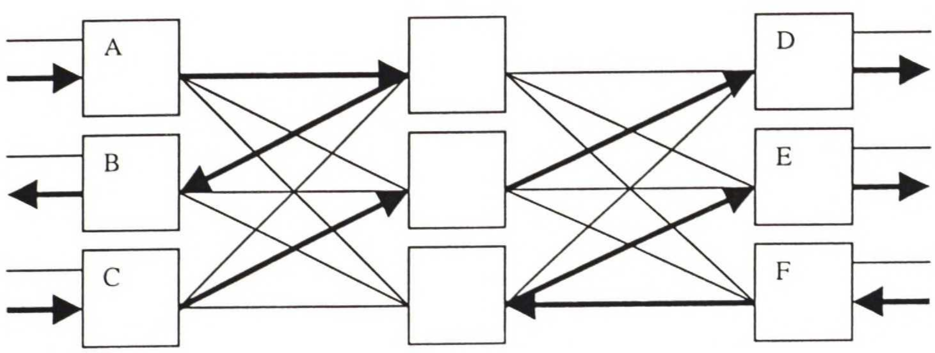


Figure 21. Strict sense non-blocking Clos network, N = 2.

When the network is folded connections like A to B and F to E should also be possible without affecting to blocking. So there should always be a free path between any free input and any free output. If connections which can be considered only in folded network are made in three stages network, how will this affect blocking. From the connections in the figure 21 (bold lines) and by the definition of the worst case connection situation it can be stated that there is always a path between outputs, whatever connections are made between the first stage nodes, third stage nodes and from the first nodes to the third stage nodes.

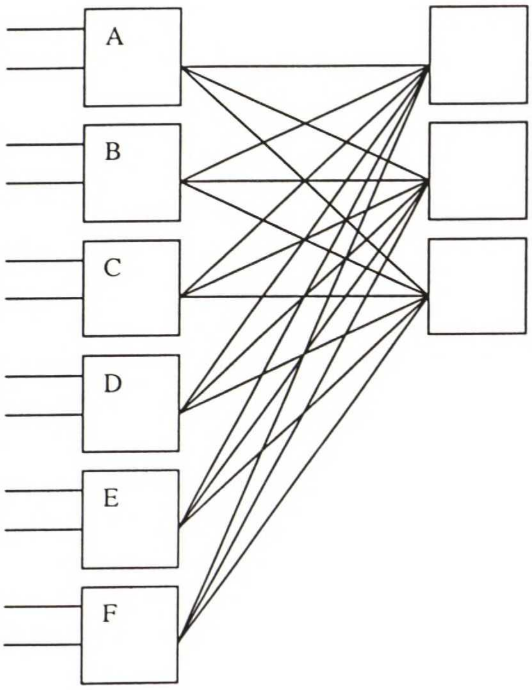


Figure 22. Folded Clos network.

7.3 Rearrangeably Non-Blocking Networks

Three stages Clos network is proved to be rearrangeably non-blocking if the amount of middle stages nodes is at least the amount of outer connections N [20]. For the rearrangeably non-blocking Clos network the number of inputs and outputs will be an integral power of the size of the switch used. Networks of other sizes can be made by carrying out reductions on the network. A reduction reduces the number of inputs and outputs by one. A reduction requires a definition of a so called frozen switch. In a frozen switch the links, which pass through the network are not affected if a new connection is set up and network should be rearranged. To carry out the reduction arbitrary call from a network input to a network output is made through a frozen switch. Every switch the call passes through is then reduced by the size of one; the links that the call passed along are removed from the network.

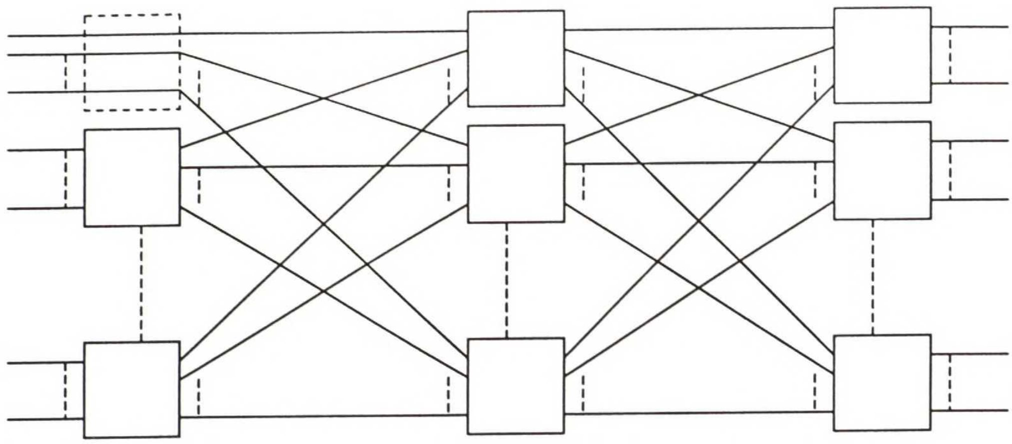


Figure 23. A 3-stage network with one redundant switch removed.

Beneš networks are created by applying the theorem that three stages Clos network is rearrangeably non-blocking if the amount of middle stages nodes is the amount of outer connections N of a switch. If the Beneš network is build from 2×2 switches, arbitrary size switches can be build by using M/2 Beneš switches for the middle stage, where M is the total amount of outer connections. This way arbitrary size of rearrangeably non-blocking Beneš network can be built. These networks are organised into $2\log_2 M - 1$ stages of M/2 switches and the total number of switches required is $M*\log_2 M\text{-}M/2$.

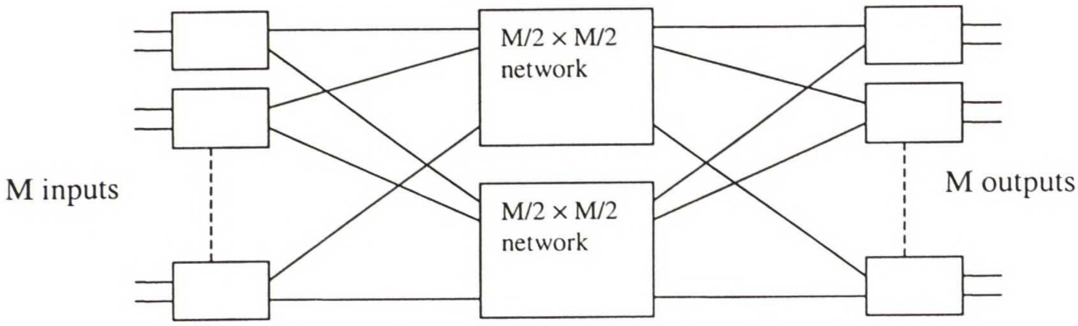


Figure 24. Recursive definition of an M × M Benes network.

A switching network which uses slightly fewer switches than the Beneš network can be constructed by using the theorem of rearrangeably non-blocking Clos networks and reduction of one input or output switch.This network arrangement is called Waksman network. The number of 2×2 switches required to produce Waksman network with

M inputs and outputs is $M*\log_2 M - M + 1$. The number of inputs and outputs in Beneš and Waksman networks must always be integral power of 2. Networks with odd number of switching elements can be constructed by using reduction.

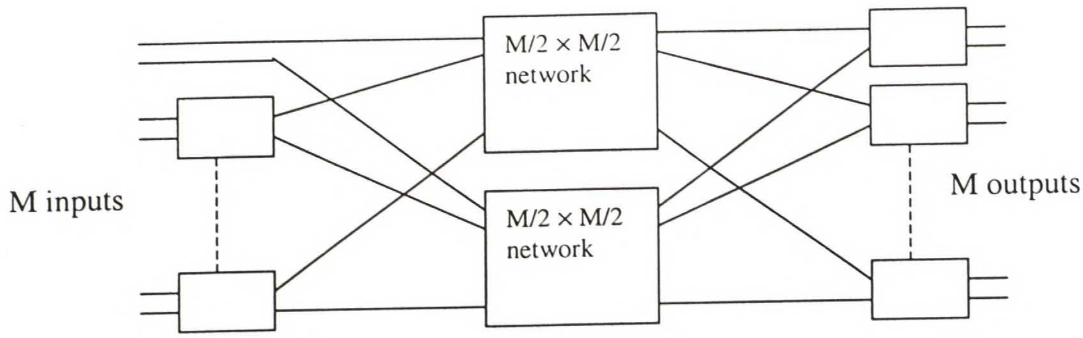


Figure 25. Recursive definition of an M × M Waksman network.

7.4 Multistage Interconnection Networks

Switching networks called multistage interconnection networks are blocking networks [20]. The interconnect field between adjacent stages in a switching network may be represented by mapping of outputs in the left-hand stage onto the inputs of the right-hand stage.

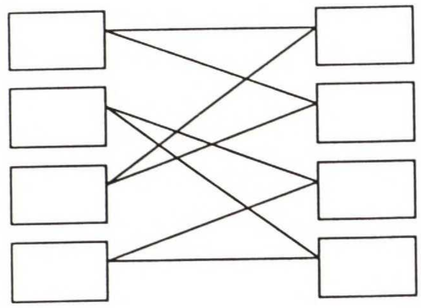


Figure 26. An interconnect between two stages.

An interconnect in figure 26 could be represented by a function I( ):

I(0) = 0

I(1) = 2

I(2) = 4

I(3) = 6

I(4) = 1

I(5) = 3

I(6) = 5

I(7) = 7

Where the number in the brackets denotes a connection from the first stage and the functions output is the input connection in the second stage. Connections with mapping function can be represented by binary representation of the connections. If the link is numbered by p = 1,2,3,...,7, the binary representation of the link is p2p1p0. For example if the link considered is the third connection between stages p = 3, the binary representation of this connection is p2p1p0 = 011, so p2 = 0, p1 = p0 = 1. The mapping function with binary representation of the connection gets now the form I(p2p1p0) = p1p0p2. Described mapping is called perfect shuffle permutation.

$$\sigma(p_{k-1}p_{k-2}\cdots p_0) = p_{k-2}\cdots p_0 p_{k-1}$$

Another important permutation is bit reversal permutation.

$$\sigma(p_{k-1}p_{k-2}\cdots p_0) = p_0 p_1 \cdots p_{k-2}$$

Baseline network is a multistage interconnection network which can be build up from 2×2 switches. A 2×2 baseline network is simply a 2×2 switch. Network with any desired size can be built by repeatedly duplicating the existing network and substituting it in the definition of figure 27.

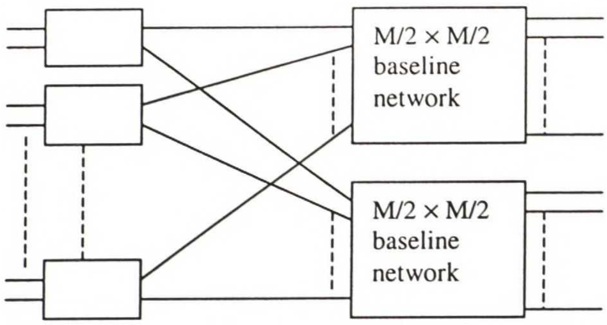


Figure 27. Recursive definition of a M × M baseline network.

8 × 8 baseline network can be constructed from 4 × 4 and 2 × 2 switching elements by recursion. Baseline network can also be defined by its interconnections like the network in figure 26. For i = 0,…,k – 2 the interconnect between stages i and i + 1 in a baseline network may be described as a permutation on the numbers 0,1,…,M – 1:

$$\beta_i(p_{k-1}p_{k-2}\cdots p_0) = p_{k-1}\cdots p_{k-1}p_0 p_{k-i-1}\cdots p_1$$

This is inverse perfect shuffle on the lower k – i bits. If M = 8, the number of stages in baseline network is three k = 3 and the interconnect between stages 0 and 1 and between stages 1 and 2:

$$\beta_0(p_2p_1p_0) = p_0p_2p_1 \qquad \beta_1(p_2p_1p_0) = p_2p_0p_1$$

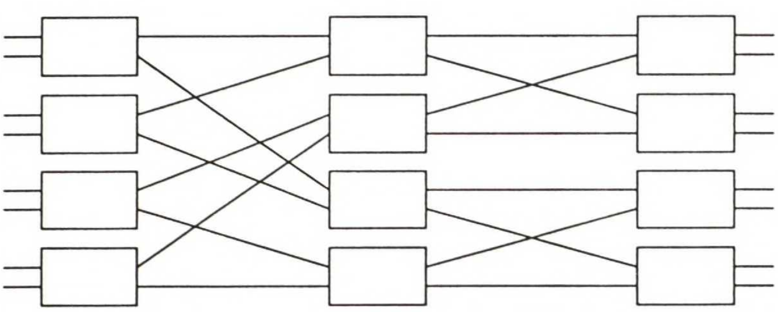


Figure 28. 8 × 8 baseline interconnection network.

Baseline networks are self-routing. This means that the setting of each switch can be made purely by examining a bit of destination of either call going through it. If the bit is '1', the call leaves through the upper output of the switch; if it is '0', it leaves through the lower output.

7.5 Sorting Networks

In a sorting network, each input is tagged with a value, and the network sorts these inputs according to the tag value [20]. A sorting network can thus be used as a switching network when each input is labelled with the output it is destinated for. Batcher sorting networks are based on well-known sort-merge procedure. These networks are self-routing and can be defined recursively. The merge networks may be implemented using Batcher's bitonic sorter. Suppose a(0), a(1),..., a(M – 1) is a bitonic sequence. Then there exist some $j \in \{0,\ldots, M-1\}$ such that $a(0) \le a(1) \le \cdots \le a(j) \ge \cdots \ge a(M-1)$. The sequence is also bitonic if it can be modified to form a bitonic sequence of above by taking $k \in \{1,\ldots,M-1)$ members from the right-hand side of the list and replacing them before the left-hand side, in the same order. For example, 1, 3, 4, 5, 6, 4, 1, 1 is a bitonic sequence. A sequence 4, 5, 6, 4, 1, 1, 1, 3 is also bitonic by definition of a bitonic sequence because 1 and 3 from the right-hand side can be moved to the left-hand side.

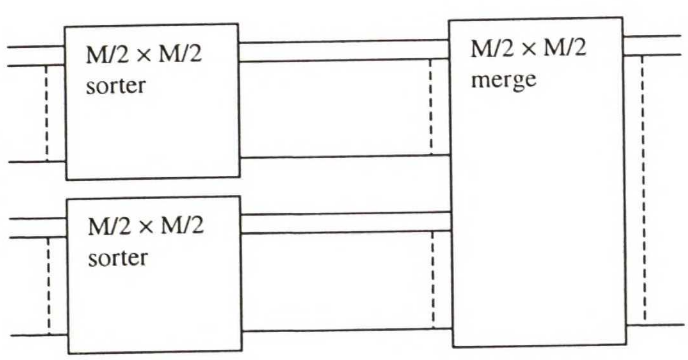


Figure 29. Recursive definition of an M × M sorter.

Merge network takes two lists from sorters, which are sorted into ascending order and combines them. A 2 × 2 sorting network is simply a 2 × 2 switch which is always set so that the element with the highest tag leaves on the lower output.

7.6 One-Sided Bidirectional Three Stages Switching Network

Strict sense non-blocking one-sided bidirectional network with three stages is possible to construct from two-stage network. The third stage is added to a strict sense non-blocking one-sided network. If the connection is made between the second and the third stage, there is always a path between any free second stages outer connection. This is due to strict sense non-blocking of two stage network. This causes an independence of the second stages switching devices outputs from which the signal is routed to the output of the first stage.

The amount of needed second stage switches is marked with L_2 and the amount of needed third stage switches is marked with L_3. The third stage to be strict sense non-blocking to every connection from the first stage can be stated as

$$L_3 = 2/Y_2 * (L_1 * Y_1 - X_2) + 1.$$

X and Y are defined as in the two-stage network. To every second stages switching element there is $L_1 * Y_1$ connections from the first stage. For the required amount of the second stage nodes can stated that if there are N – 1 connections made from a switching element to N – 1 second stage switching elements, the needed amount of second stage switching elements is N – 1 + 1, because the signal can be routed to the output switch from any of the second stage switches. If there is more than one connection line between the first and the second stage switches, the amount of second stage nodes is

$$L_2 = 1/Y_1 * (N - X_1) + 1.$$

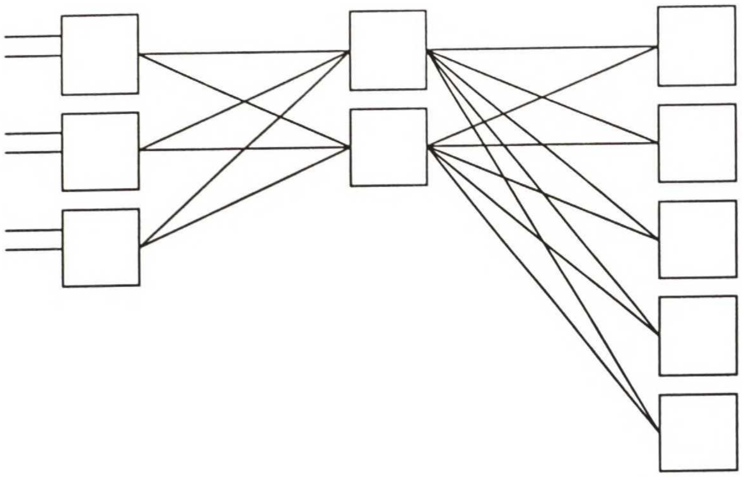


Figure 30. Three stages one-sided bidirectional switching network.

The number of switching elements in the second stage depends on the outer connections of the first stage and the number of switching elements in the third stage depends on the amount of the first state switching elements. It can be noticed from the figure 30 that $L_1*N = L_2*L_1$, so the outer connection capacity from the second stage is the same than the outer connection capacity from the first stage, although switching is divided to several switching elements. The outer connection capacity of the first stage is considered as the switching capacity of the whole system. More generally outer connections from the second stage are $L_2*L_1*Y_1$. The whole system capacity is greater than the second stages outer connections when $L_1*N > L_2*L_1*Y_1$ -> $N > N - X_1 + Y_1$ -> $Y_1 < X_1$. By the definition of X_1 this never occurs.

The amount of the first and the second stage switching devices in the network architecture can be stated as

$$L_2 + L_3 = 1/Y_1 * (N - X_1) + 1 + 2/Y_2 * (L_1 * Y_1 - X_2) + 1 = \frac{N}{Y_1} - \frac{X_1}{Y_1} + \frac{2 * L_1 * Y_1}{Y_2} - \frac{2 * X_2}{Y_2} + 2.$$

If the first stages devices capacity N is solved the equation is

$$N = Y_1 * (L_2 + L_3 + X_1 / Y_1 - 2 * L_1 * Y_1 / Y_2 + 2 * X_2 / Y_2 - 2)$$
$$= Y_1 * L_2 + Y_1 * L_3 + X_1 - 2 * L_1 / Y_2 * Y_1^2 + 2 * X_2 / Y_2 * Y_1 - 2 * Y_1.$$

N is differentiated with respect to Y_1 and the zero point is searched

$$\frac{dN}{dY_1} = L_2 + L_3 - 4 * L_1 / Y_2 * Y_1 + 2 * X_2 / Y_2 - 2$$
$$L_2 + L_3 + 2 * X_2 / Y_2 - 2 = 4 * L_1 / Y_2 * Y_1$$
$$Y_1 = Y_2 / (4 * L_1) * (L_2 + L_3 + 2 * X_2 / Y_2 - 2)$$
$$= 1/(4 * L_1) * (L_2 * Y_2 + L_3 * Y_2 + 2 * X_2 - 2 * Y_2).$$

This is a maximum value for N because the second derivative is negative.

Because the amount of the third stage devices depends on the product $L_1 * Y_1$, the structure of the first and the second stage can be repeated by increasing the switching capacity of the third stage devices.

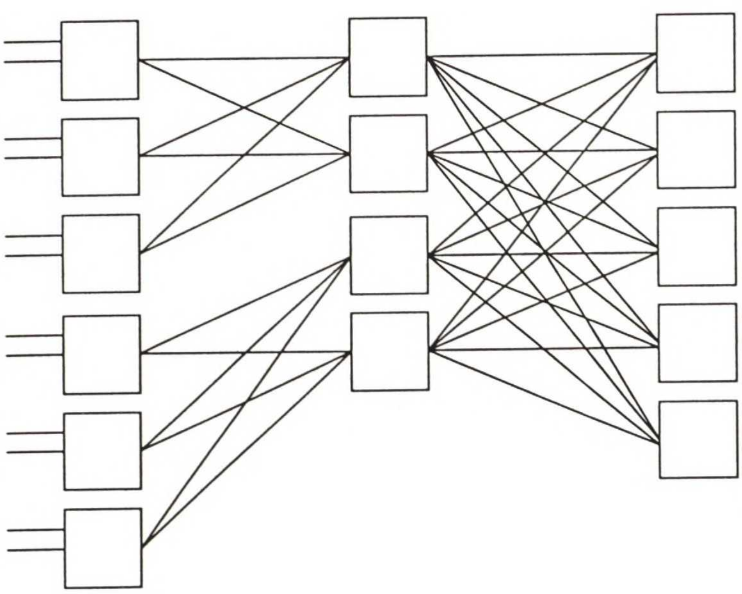
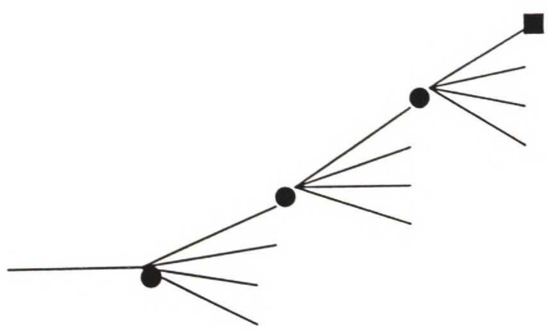


Figure 31. Duplication of the first and the second stages.

The network is strict sense non-blocking to every connection between inputs of the network.

7.7 Switched optical access network

Optical switching network architectures considered earlier in the chapter are used to construct optical switching devices and cross connection devices. Access network can be constructed from remote access nodes consisting of switching devices from which data is switched to optical network units. Switched optical access network can be for example arranged like PON tree structure. Optical access is provided by switching devices located in remote access nodes. Remote access nodes devices can be used for IP packet switching.



- ● A remote access node consisting of switching devices.
- ■ Optical network unit

Figure 32 . A three stages SOAN arranged in tree structure.

8 Simulations

Access networks are simulated with simulation tool VPI transmission maker. Optical and electrical signals are represented as computer data that is exchanged between interconnected modules via a simulation environment adaptation layer [21]. Two representations of signals are block mode and sample mode, which describe how data is passed between modules and how data is processed by the modules. In the block mode signal information is delivered to each module unidirectionally so a simulated module affects to signal once and passes it to the next module. A block of signal data represents tens of bits of data [22]. In the sample mode the simulation is carried out iteratively. The result of simulation is achieved by passing subpicosecond slices of time between modules. Simulation is done bidirectionally so subpicosecond slices of time are passed between all the modules until the final state of the simulation is reached.

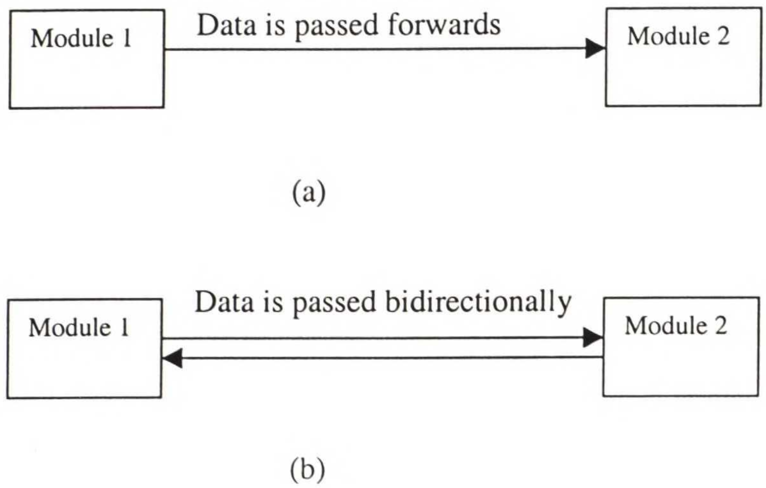


Figure 33. Two modes of signal representations in VPI transmission maker (a) block mode (b) sample mode.

There are four simulations considered in this part for future access network. A simple passive optical network which simulates broadcasting of data to sixteen optical network units with no upstream channel. Transmission module is considered as a broadcasting unit from local exchange. Broadcasting signal could be for example CATV or DTV signal delivered to a small amount of customers via optical fibre links. Signal is first delivered to splitter with optical fibre link. With the splitter it is possible to divide the signal power to many parts having possibly unequal signal powers depending on fibre optic link distances after the splitter. Again signal is delivered to the second splitter with fibre optic link. The second splitter is considered as ONU of the simulated PON access network. Optical signal is then converted to electrical, which can be for example DTV signal or Internet traffic. Two transmission paths are compared and the aim is to provide equal service to both braches. This is achieved by sending more signal power to path where is more attenuation caused by distance or fibre characteristics. SuperPON simulation describes access network with longer distances and higher data rates. Signal power is amplified after splitting and after certain amount of transmission distance. Amplifiers are spaced to provide equal service to two transmission branches. Optical switching access network is tree network. Transmission between central office and optical network unit is provided by remote access nodes, where the data is routed to a specific destination. Another switching network is a mesh access network with protected path considered. Network can be formed by point to point links from optical network units.

8.1 Passive Optical Network

Data rate of the PON simulation is 155 Mbit/s, which is considered suitable for small offices and homes. The head end is sending a pseudo random binary sequence (PRBS) with possibility to define the probability of '1's. The data stream is sent through optical fibre link to distribution point, where the signal power is split. The length of the optical fibre is at most 5000 m and attenuation of the fibre is 0.2 dB/km. Another fibre parameter considered is dispersion, which causes broadening of the optical signal. From the first splitter the signal is delivered to two branches. The other is considered as an aerial distribution fibre over 10000 m distance and the other as an optical link of 5000 m. Attenuation and dispersion parameters of aerial fibre are chosen to higher values, because of aerial distribution characteristics. Attenuation of the aerial optical link, which is delivered with power cables is 1.0 dB/km and dispersion $20*10^{-6}$ s/m^2. Dispersion is defined as group velocity changes in a function of frequency. The parameters for the other link are 0.2 dB/km and $16*10^{-6}$ s/m^2. The aim is to choose the power splitting factor of the first splitter to ensure equal quality services to both branches. Optical to electrical conversion is done by the photo diode and the electrical signal is monitored with scope. Electrical signal to noise ratio is measured after each photo diode.

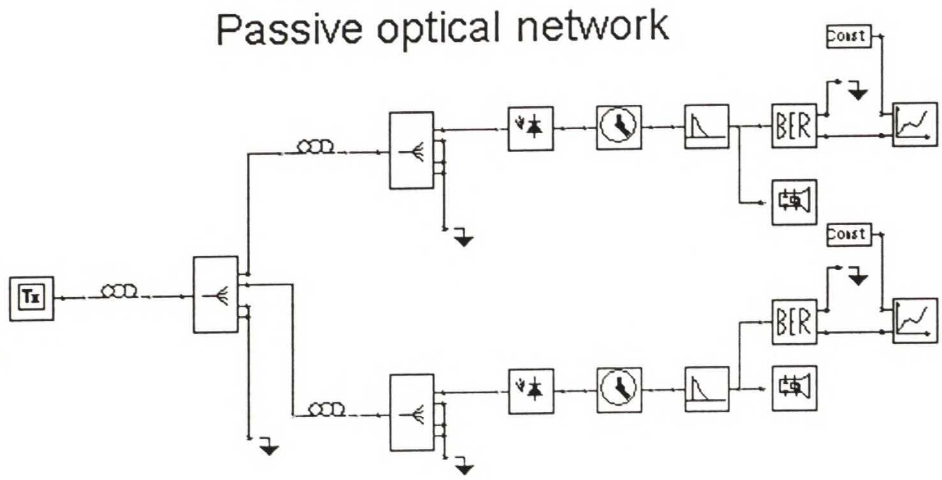
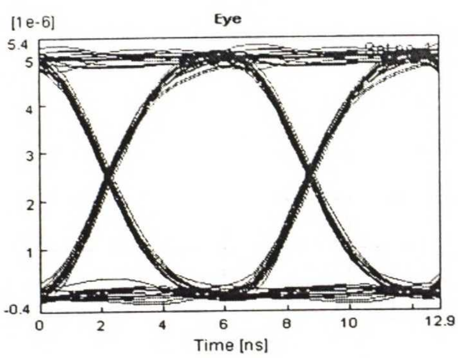


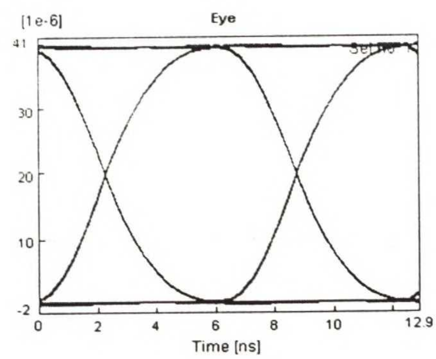
Figure 34. Simulation setup for passive optical network.

In figure 35 is graphical presentation of the eye diagrams after transmission when the first splitter is dividing the signal power equally between two branches. Q for the aerial distribution was measured to 27.5 and for the other branch Q = 50.0. Q value of simulation is defined in appendices. The ratio between the two Q values is

$$\frac{Q_1}{Q_2} = 0.55.$$



(a)



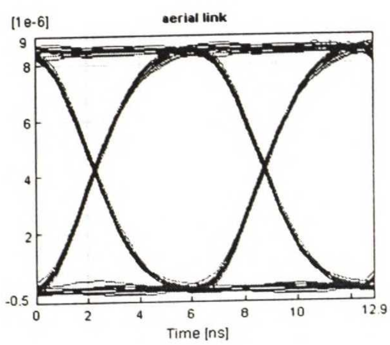
(b)

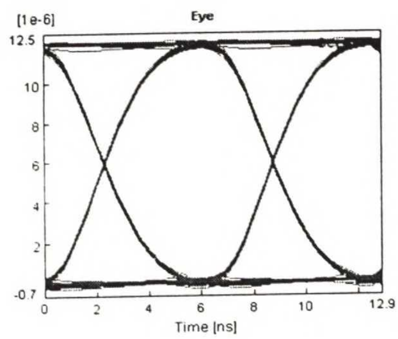
Figure 35. (a) aerial distributed data sequence, (b) data sequence transmitted over other link.

By choosing the splitting factor of the first splitter properly the Q values of the two branches is equal or ratio between the two Q values is close to one, when the received signal powers are equal. With the splitting factor is 0.15 the ratio of Q values is

$$\frac{Q_1}{Q_2} = 0.92$$

The signal power arriving to the first splitter is divided so that the upper aerial distribution branch gets 0.85*(arriving optical power) and the lower distribution branch 0.15*(arriving optical power). Eye diagrams are presented in figure 27.





(a) (b)

Figure 36. Data sequences transmitted with unequal splitting factor.

Another property considered in PON simulation is the Q value, when the data rate is increased. The splitting factor of the first splitter is 0.15, which was producing enough signal power to both braches with required service rates, when data rate was 155 Mbit/s. Data rate is increased to value 2.5 Gbit/s, which can be considered as 16 time division multiplexed 155 Mbit/s signals and Q values for each branches are illustrated.

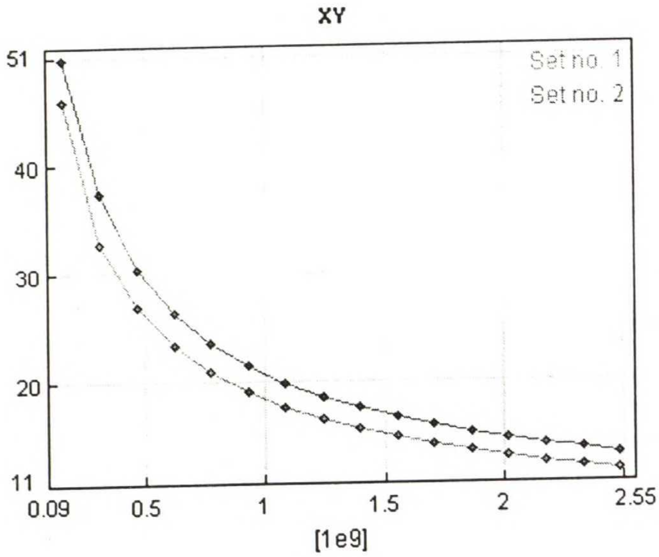


Figure 37. Q values for different data rates.

It can be noticed from the figure that with higher data rates the Q values for links are almost equal.

8.2 SuperPON

SuperPON access network architectures with optical amplification can be used with longer transmission distances and to serve more customers. Also higher transmission bit rate can be used. In SuperPON simulation two channel WDM-transmission is considered with the same kind of two-stage tree network architecture as in PON simulation. Optical amplification is used to compensate the power loss due the attenuation of the optical fibre and splitting. Amplification is done with ideal optical amplifier with wavelength independent gain. Data rate of the signal is 2.5 Gbit/s, which can be considered as 16 time division multiplexed 155 Mbit/s signals for small offices or homes. The amount of optical network units served when WDM signal is transmitted with access network architecture is 512. For WDM transmission channel spacing of 100 GHz is used. Data is transmitted from CO to the first splitting unit by optical link with optical amplification after 40 km fiber optic link. Amplification of the amplifier after the link is 10 dB. After each amplifier amplified spontaneous emission ASE noise component is added to signal. Fiber attenuation is 0.2 dB/km and dispersion $16*10^{-6}$ s/m^2. After the first splitter there is a fiber optic link of 300 km distance. Optical repeater units, which contain optical amplification are placed after 30 km section of transmission. Amplification of ORU amplifiers is 5 dB.

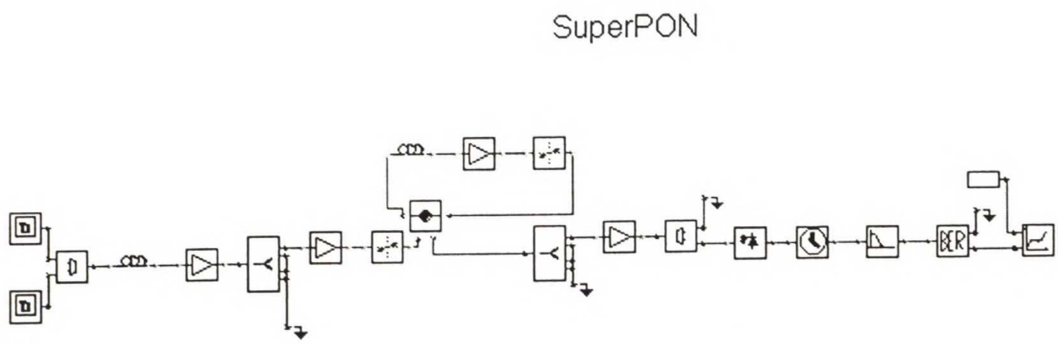


Figure 38. Simulation setup for SuperPON.

The link distance between the first and the second splitter is increased from 30 km to 300 km and Q value is measured from the other of the WDM channels.

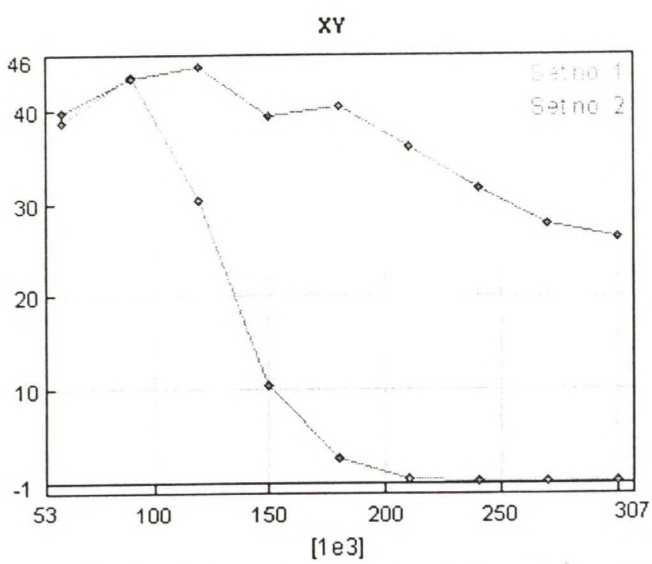


Figure 39. Q values for WDM channels with amplification and without amplification.

For comparison the Q value without amplification is also simulated and it can be noticed that after 200 km the signal is probably too bad for detection but amplified signal quality is retained. Over 300 km link distance can be needed for some rural area applications [23]. Powering is needed for optical repeater units.

8.3 Switched Optical Access Network

For a switched optical access network the tree network structure is considered, where there are several remote access nodes.

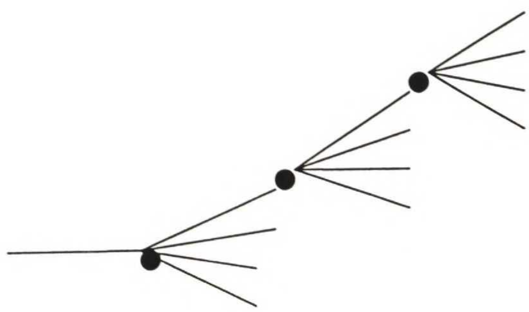


Figure 40. Illustration of simulated switching network

The data rate of the simulation is 2.5 Gbit/s and two channel WDM transmission is used. The initial amount of remote access nodes is one. The distance between remote access nodes is 5000 m and insertion loss of the switch is 1.2 dB and crosstalk 40dB [12]. The BER value of the transmitted data sequence is estimated, when the amount of remote access nodes is increased to the final amount ten. Remote access nodes are considered to consist switching devices of multiples of 2×2 switching elements describing a route through a switch. The initial amount of switching elements in a switching device is one and the final amount is five describing a five stages switching network. Switching architecture can be strict sense non-blocking network, rearrangeably non-blocking network or blocking interconnection network. When rearrangeably non-blocking network is considered with five switching stages it is possible to construct a 8×8 switching device. A blocking baseline network constructed from five stages is a 32×32 switching device.

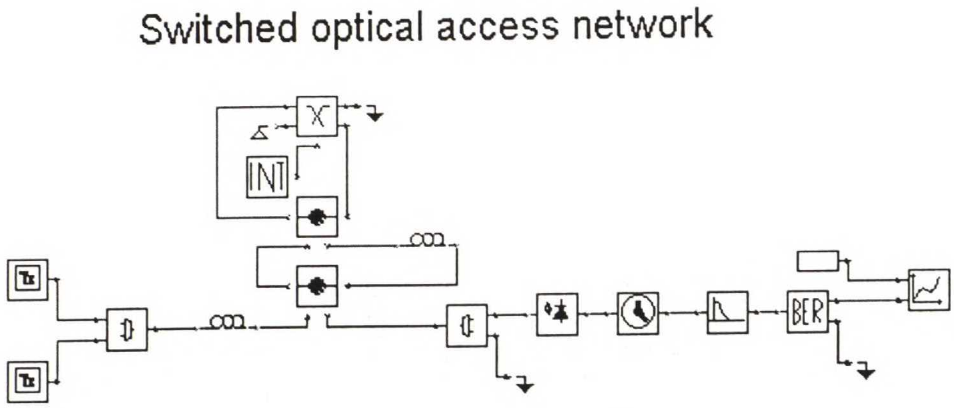


Figure 41. Simulation setup for switched optical access network.

The estimated BER curve is illustrated in figure 33. SOAN constructed from three remote access nodes and 32 × 32 baseline switching networks in a remote access node can serve over 30000 optical network units. If 4 × 4 rearrangeably non blocking switching networks are used in remote access nodes and SOAN is constructed from five remote access nodes the amount of served optical network units is 1024. 8 × 8 rearrangeably non blocking switching networks used in three remote access node SOAN can serve 512 optical network units.

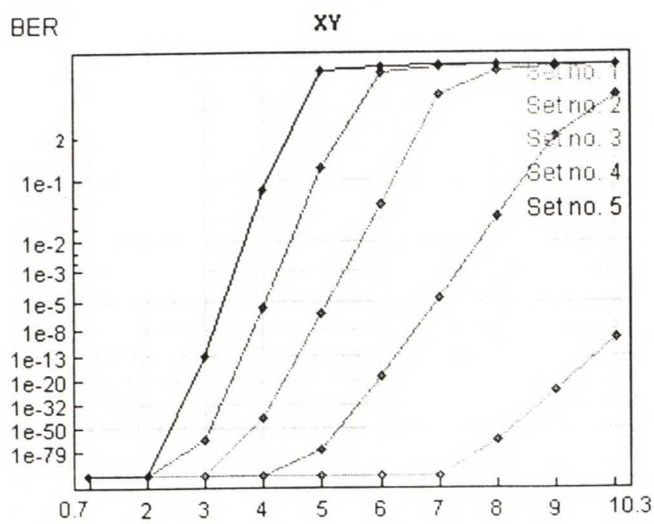


Figure 42. BER of simulated switched optical access network.

8.4 Protected mesh network

For switched optical access network simulation a protected network is considered, where there are several paths through access network to specific ONU. If there is a failure in transmission, the data can be switched from some other path to the ONU. A simulated network can be considered as a mesh network, where ONUs are connected as in figure 43. Network could be constructed from point to point links to rural area telecommunication services delivery.

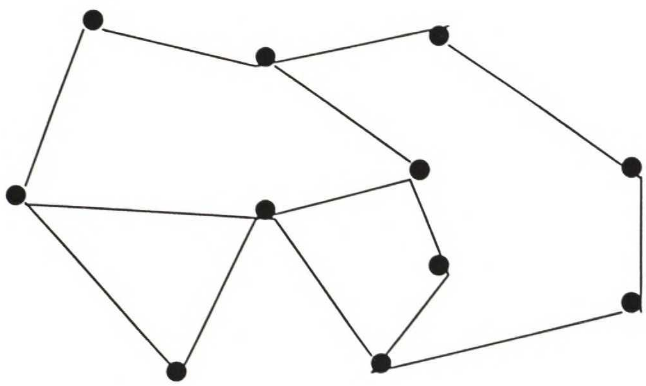


Figure 43. A mesh access network, where ONUs are connected with several paths.

If there is a failure in transmission in one path the data can be routed to the destination ONU with some other link. A failure in transmission can be caused for example by a fiber cut or a switch failure. In a simulation set up two paths are considered through the network. One is the actual path and the other is the protecting path with longer distance and more switching elements along the path. Data rate of the simulation is 2.5 Gbit/s, which can be considered as 16 TDM signals of 155 Mbit/s and two channel WDM transmission is used. The amount of served ONU varies, because there is no specific path to the every ONU, but the data is switched from the arriving signal to ONU. 1 + 1 protection is used [24], which means that the same data is send twice to the destination ONU through different paths. Protecting switching is done with protecting switching module with external control. The protected path is considered to consist of three switching stages and the distance between the stages is 15 km. The protecting path has four switching stages with distance 15 km. With oscilloscope module it was measured that the data from protection path arrives to the ONU 25.6 ns later than from protected path.

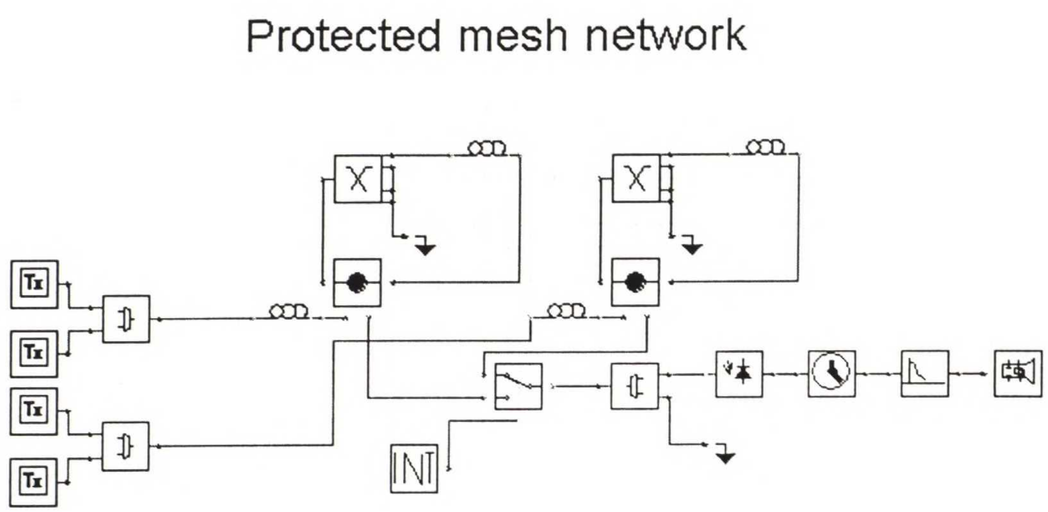


Figure 44. Simulation set up for protected mesh network.

9 Conclusions

With optical access network it is possible to increase data rates that existing access network can provide. Passive optical network uses passive optical components like power splitters to divide the signal to customers. Optical amplification can be used for longer transmission distances. Along-the-route-Branched Passive optical network is suitable access network for small offices and private home areas. Signal is branched using standard fused fibre couplers with coupling ratio 10/90 or 20/80. Passive optical network, which routes wavelengths to optical network units has no power splitting and this way larger access network can be constructed. Arrayed waveguide gratings is a device routing wavelengths from input ports to output ports. SuperPON demonstrator uses optical amplification to splitting factor 2048 and a span of 100 km. Amplifiers like semiconductor optical amplifiers are housed in optical repeater units. SuperPON can be more economical alternative than PON if costs of optical components decrease.

Switched optical access network uses management information to define a route from central office to optical network unit. Management information is used to control switches housed in remote access nodes. Switching devices are usually constructed from 2×2 switches. Switching network architectures can be used to construct switching devices over 100×100. An important feature of a network architecture is blocking. Networks can be divided to strict-sense nonblocking, wide-sense nonblocking, rearrangeably nonblocking and blocking networks.

Passive optical network is simulated, where signal is branched by splitting signal power with ratio 15/85. Signal quality is demonstrated by presenting eye diagrams. Q value dependence of data rate is also simulated for different branches. In SuperPON simulation Q value of an amplified signal is compared to a signal without amplification when a span is increased to 300 km. Switched optical access network simulation considers access network capacities, measured by served optical network units and span, for switching network architectures with different blocking characteristics. Protected path simulation demonstrates delay caused by switch failure or fiber cut. Data is sent with two paths to destination optical network unit and each link between remote access nodes causes delay time.

References

[1] Chand Naresh, Magill Peter D., Swaminathan Swami V., Daugherty Thomas H. Delivery of Digital Video and Other Multimedia Services (>1 Gb/s Bandwidth) in Passband above the 155 Mb/s Baseband Services on a FTTx Full Service Access Network.

[2] Volotinen Tarja T. An integrable and cost effective FTTH-network structure.

[3] Kos Tomislav, Zovko-Cihlar Branka, Grgic Sonja. New Services over CATV Network.

[4] Kuri Josué, Gagnaire Maurice. ATM Traffic Management in an LMDS Wireless Access Network.

[5] Ramaswami Rajiv, Sivarajan Kumar N. Optical networks: a practical perspective.

[6] Maier Guido, Martinelli Mario, Pattavina Achille, Salvadori Elio. Design and cost performance of the multistage WDM-PON access network.

[7] Wellen Jeroen, Smets Rob, Van Ooijen Gijs, Van der Steen Dick, Steenbergen Kees, Janssen Fons, Nicolas Christophe. Fast optical switching in WDM passive optical access networks.

[8] Giles C.R., Doerr C., Zirngibl M., Joyner C., Koren U., Dryer K.F., Zyskind J., Sulhoff J., Stulz L., Wolf C. 1.8 Petabit/s downstream capacity WDM passive optical network.

[9] Van de Voorde I., Martin C. M., Vandewege J., Qiu X. Z. The SuperPON demonstrator: An exploration of possible evolution paths for optical access networks.

[10] Nakajima Hirochika. Development on Guided-Wave Switch arrays.

[11] McGreer Kenneth A. Arrayed Waveguide Gratings for Wavelength Routing.

[12] Marxer Cornel, de Rooij Nicolaas F. Micro-Opto-Mechanical 2 × 2 Switch for Single-Mode Fibers Based on Plasma-Etched Silicon Mirror and Electrostatic Actuation.

[13] Kim Jin Young. Performance of an Optical CDMA System with Turbo Code.

[14] Mendez Antonio J., Gagliardi Robert M., Feng Helena X. C., Heritage Jonathan P., Morookian John-Michael. Strategies for Realizing Optical CDMA for Dense, High-Speed, Long Span, Optical Network Applications.

[15] Matsutani Hideyuki, Nakagawa Masao. Multi-Carrier DS-CDMA Using Frequency Spread Coding.

[16] Hui R., Zhu B., Huang R., Allen C., Demarest K., Richards D. 10 Gb/s SCM Fiber System Using Optical SSB Modulation.

[17] Hill Paul M., Olshansky Robert, Burns W.K. Optical Polarization Division Multiplexing at 4 Gb/s.

[18] Kabacinski W., Danilewicz G. Wide-Sense Non-blocking Multi-Log_2N Broadcast Switching Networks.

[19] Kabacinski W. Non-blocking Folded Architectures for Multirate ATM Switching Fabrics.

[20] Hunter David K. A Tutorial Introduction to the Theory of Space Switches.

[21] Mutafungwa Edward. A Study of Switched Optical Access Networks.

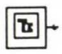
[22] Virtual Photonics. VPItransmissionMaker™ WDM User's Manual.

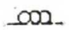
[23] Levieux Craig. The Use of Optical Fibre to Provide Economic Telecommunications in Rural Areas.

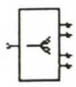
[24] Sengupta Sudipta, Ramamurthy Ramu. From Network Design to Dynamic Provisioning and Restoration in Optical Cross-Connect Mesh Networks: An Architectural and Algorithmic Overview.

Appendices

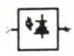
Modules

 Externally modulated laser transmitter

 Nonlinear dispersive fiber

 Power splitter 1-4

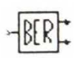
 Ground

 Photodiode PIN

 Clock recovery ideal

 Filter LP Bessel

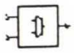
 Time domain visualizer (scope)

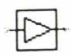


BER estimation

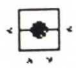
 Const

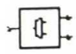
 Visualizer XY

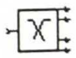
 WDM MUX 2-1

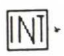
 Ideal amplifier with wavelength independent gain

 Linear polarizer ideal

 Ring initialization (loop)

 WDM DEMUX 1-2

 Y DOS switch 1x4

 Integer source

 Protection switch

BER estimation in VPI transmission maker

BER is estimated indirectly, usually by measuring the Q value of the system by assessing the sensitivity of a system to changing the 1/0 detection threshold. Q can also be used in simulations, and the BER module outputs the sensitivity to changing the received threshold.

The BER can be easily related to Q by:

$$BER = \frac{1}{Q\sqrt{2\pi}} \exp(-\frac{Q^2}{2})$$

The Optical Signal to Noise Ratio (OSNR) can be used as a first estimate of the Q value of the received bits. This is valid if the system has no eye closure from other effects, such as dispersion, nonlinearities etc. The following equation relates logarithmic Q to OSNR

$$Q = 20\log\left(\frac{2.0 \times OSNR\sqrt{\frac{B_0}{B_e}}}{1 + \sqrt{1 + 4.0 \times OSNR}} \right)$$

where: B_0 is the optical bandwidth of the receiver, and B_e is the electrical bandwidth of the receiver's post-detection filter. For reasonable OSNR values (>10 or 10 dB), this equation approximates to:

$$Q = 20\log\left(\sqrt{OSNR}\sqrt{\frac{B_0}{B_e}} \right)$$

which equals,

$$Q = 20\log\left(OSNR\frac{B_0}{B_e} \right)$$

or in dB units for OSNR:

$$Q = OSNR + 10\log\left(\frac{B_0}{B_e}\right)$$

This suggests the Q increases as the optical bandwidth is increased. This is simply because the OSNR is integrated over the receiver bandwidth, and it is the power spectral density of the noise which dominates the receiver's sensitivity for reasonable OSNR values.

Costs of optical components

Gould fiber optics:

Wavelength Independent Coupler

Wavelength 1550nm

1×4

Insertion loss ≤ 7.0 dB

250 Euros

Wavelength division multiplexer

Wavelength 1550nm

Insertion loss ≤ 0.5dB

Bandbass $\pm$ 20nm

570 Euros

Fiber amplifier

Wavelength 1550nm

1000 Euros